

The University of Chicago

UPPER-AIR TRAJECTORIES AND WEATHER FORECASTING

A DISSERTATION SUBMITTED TO THE FACULTY OF THE
DIVISION OF THE PHYSICAL SCIENCES IN CANDIDACY
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF METEOROLOGY

By
DAVE FULTZ

Reprint of
THE UNIVERSITY OF CHICAGO
DEPARTMENT OF METEOROLOGY REPORT No. 19
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INTRODUCTION

This is a report on an attempt to improve forecasting of the surface and upper pressure distributions by means of a trajectory technique applied primarily to the 10,000-foot chart in co-ordination with such other aids as are ordinary or were found useful. The project was initiated by Professor C.-G. Rossby of the University of Chicago to develop practical means of utilizing prognostically the paths of particles in the free atmosphere as computed from the assumption of constant absolute vorticity. These paths on the 10,000-foot chart, which was chosen for the first extensive trials partly because several preliminary cases seemed to show promise, were used to find an approximation to the velocity pattern at some future time as an aid to drawing the prognostic 10,000-foot pressure pattern and thence to forecasting the surface map.

One series of maps was drawn at the Central Office of the United States Weather Bureau in Washington, D.C., during July, 1942, and a second series was begun in August, 1942, at the Weather Bureau Airport Station at Chicago, Illinois; these form a more or less continuous map file up to June, 1943.¹ Though this period is rather short, it is felt that conditions were sufficiently representative to allow some general conclusions.

It is intended in the paper to give some of the theoretical principles involved, an idea of the procedure as developed to date, some empirical ideas which seem to be useful, and an account of the verification obtained. This material should serve to indicate under what circumstances profitable use can be made of the full procedure and, where that is impracticable, what additional indications may be derived from a careful inspection of the ordinary charts with the ideas herein expressed in mind.

A work of this kind is necessarily the product of many hands, but especially so in synoptic meteorology, whose very existence depends upon the co-operation of many thousands of observers and workers the world over. In the present instance, the original idea and theoretical development are due to Professor Rossby, from whom also have come several of the suggestions concerning synoptic applications. Many others have contributed ideas, suggestions, and effort to the project; of whom H. G. Dorsey, Jr., and

¹Hereafter, unless other years are given, dates will refer to the period August, 1942, to June, 1943, inclusive.

J. Namias at Washington and G. E. Dunn, H. L. Jacobson, V. J. Oliver, R. C. Schmidt, and S. Teweles at Chicago should be mentioned. To these and to a half-score more who have helped with the job, the author expresses his best thanks.

To the United States Weather Bureau the project is indebted for loans of facilities and personnel without which the work could not have been carried on. The author further wishes to thank Professor H. R. Byers, Mr. G. W. Platzman, Mr. H. Riehl, and Professor V. P. Starr for extremely helpful comments and criticism during the preparation of the report.

CHAPTER I

THEORETICAL PRINCIPLES

This paper, which will attempt to give some useful forecasting principles, would have to be an encyclopedia if it attempted to present everything which has some value for the forecast problem, or even everything which has gone on in our minds in trying to forecast. It will have to be restricted, therefore, primarily to considerations bearing on the trajectory principle and secondarily to related ideas which we have happened particularly to notice. The reader will be able both to judge these considerations and to supply others of his own from map experience. For purposes of a beginning, we will consider in this chapter some elementary hydrostatic ideas which bear upon the procedure, the kinematic behavior of certain wave patterns, and the trajectory principle.

1. Hydrostatics

The hydrostatic principle may be stated as

$$dp = -g\rho dz,$$

where these symbols have their usual meaning. One of the most obvious of the implications of this equation, since the density is inversely proportional to the temperature, is that the pressure will fall more rapidly with height in a cold region than in a warm one. Thus, for example, if a surface high is centered over the Middle West in such a way that New Orleans and Winnipeg have the same surface pressure, because of the prevalence of a south-to-north temperature gradient the upper pressures at New Orleans will almost invariably be higher than at Winnipeg. This also means that, even if at some one time the surface pressure were to be everywhere the same, the ever present temperature contrasts would lead to pressure gradients aloft and corresponding circulations. If the upper winds do not flow parallel to the isotherms at their particular level, they would change the temperature distribution aloft, and this in turn would alter the surface pressures. The integrated effect of these temperature and circulation changes at all levels is an important part of the weather which we observe.

The pressure changes at various levels at a fixed place which result from these circulations can be of a number of types, some of which we can describe briefly and which are often of help in interpreting synoptic changes.

A simple case is one which occurs fairly often when a strong high is lying along the eastern seaboard of the United States. In the strong southerly flow to the west of the high, the mean temperature of the column between 10,000 feet and the ground at a station like Louisville will rise rapidly, while the surface pressure will change little or not at all. The result is a large rise in the 10,000-foot pressure. Now, from Bjerknes' tendency equation,¹ the pressure tendency at a height h is given by

$$\left(\frac{\partial p}{\partial t}\right)_h = - \int_h^\infty g(\underline{c} \cdot \nabla_2 \rho) dz - \int_h^\infty g\rho(\nabla_2 \cdot \underline{c}) dz + g(\rho w)_h. \quad (1)$$

Several mechanisms can thus be imagined to produce the above sort of change. These are given alone or in combination by the three terms on the right of this equation which are, in order, (1) horizontal advection, (2) horizontal convergence or divergence, and (3) vertical mass displacements. For instance, suppose that the horizontal advection and the horizontal divergence terms are both zero above 10,000 feet. This upper column, then, will remain unaltered, and any pressure rise at 10,000 feet would be produced by the vertical velocity term; that is, it would be as though the original column between 10,000 feet and the surface were replaced by an expanded column of the same weight, since the surface pressure is unchanged while the column above remains completely unaltered. At levels above 10,000 feet, since the whole upper column would be lifted by the same geometrical amount, the pressure rises would become less and less as the density of the air decreased upward. Suppose, however, that there is no vertical movement through the 10,000-foot level as the column below becomes warmer and lighter. Then, if the surface pressure is to remain the same, advection of heavier air or convergence into the upper column or suitable combinations of these must take place. In these cases, while the 10,000-foot rise will be the same provided the temperature change below is the same, the other upper pressure changes will show a different pattern than in the first case. The converse of these changes occurs at certain stages in some cold-air outbreaks when advection of cold air in the low levels will occur with lowering of the 10,000-foot pressure and little change in the surface pressure.

Let us further consider one or two other relatively simple cases. Suppose that within a restricted range of height there is advection of

¹J. Bjerknes, "Theorie der aussertropischen Zyklonenbildung," *Met. Zeitschr.*, Vol. LIV (1937). Also M. Margules, "Über die Beziehung zwischen Barometerschwankungen und Kontinuitätsgleichung," *L. Boltzmann Festschrift* (Leipzig: J. A. Barth, 1904).

heavier air over a given place with no change in the column above that height and only the effects of compressibility in the column below. Suppose, further, that the new air is "a" millibars heavier than the air column of the same height which it is replacing. Then, since the weight of the rest of the column is unaltered, a rise of "a" mb will occur at the surface. The column below the advective zone will be compressed by the greater weight above it so that air will sink through fixed levels with an accompanying tendency toward pressure falls. The pressure changes at fixed levels will then, with increasing height, decrease from the rise of "a" mb at the surface to actual falls, these falls reaching a maximum in the vicinity of the advective zone. Above that zone the falls will diminish owing to the lesser densities where the upper part of the column has merely dropped a constant distance at all heights.

Now suppose that horizontal divergence takes place in a similar restricted zone sufficient to remove "b" millibars of air without change in the sections of the column above and below. Then the lower column will expand, and the pressure fall of "b" mb at the surface will decrease with height due to this expansion. Whether there will be falls or rises, produced by vertical motion, in the upper column then depends upon whether the rise in height of the lower column is less or greater than the reduction in height of the divergent zone.

Complicated cases involving several zones with different advection and divergence of different signs may be difficult to recognize unless a mathematical technique such as that proposed by Rossby is used.² The latter, however, interprets all the changes of pressure as owing to horizontal advection. This is not very serious, provided one does not forget that the changes are not necessarily due to this factor alone and may have to be interpreted on the other bases also.

An application of hydrostatic principles which has been used in the forecast technique is the determination of the mean virtual temperature of an air column from the pressures at fixed levels at the top and bottom—the levels in our case being sea level and 10,000 feet. The pressure at these levels at a given point will determine uniquely a mean virtual temperature for the column of air at that point. The relation between the two pressures and the mean temperature can be expressed in the form of a graph³ which makes

²C.-G. Rossby, "Zustandsänderungen in atmosphärischen Luftsäulen," Beiträge zur Physik der freien Atmosphäre, Vol. XIII (1927); see also H. Ertel and Sjan-zsi Li, "Die Berechnung der Advektion," Met. Zeitsch., LII (1935), 356.

³V. P. Starr, Basic Principles of Weather Forecasting (New York: Harper & Bros., 1942).

possible rapid calculation. This is a means of making a rigid connection between the 10,000-foot and surface pressure maps, since, of the three variables, any two will determine the third.

2. Kinematics

From a set of simple assumptions Rossby has derived a number of purely kinematic properties for a uniform west-wind belt which is perturbed into a train of sine waves given by the following velocity equations⁴ in which u is the west-wind speed, v is the south-wind speed, L is the wave length, c is the wave velocity, t is the time, and x is positive toward the east:

$$u = U = \text{constant}, \quad v = v_0 \cos \frac{2\pi}{L}(x - ct). \quad (2)$$

The chief of these assumptions are that there is horizontal motion only; that individual air parcels conserve their temperature; that the temperature distribution is steady with respect to a co-ordinate system moving with the wave velocity, c ; and that the meridional temperature gradient is a constant. If these waves are to travel without change in shape as required by the assumptions, the analysis leads to the result that

$$\frac{A_T}{A_S} = \frac{U}{U - c}, \quad (3)$$

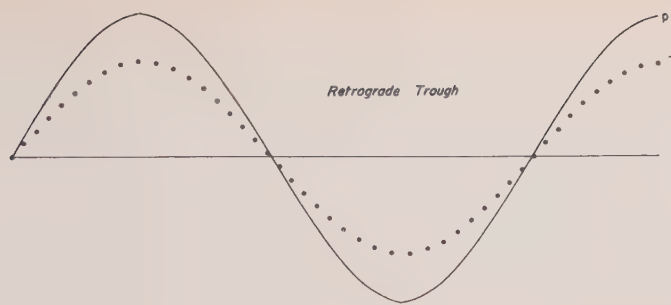
where A_T is the amplitude of the isotherms (and incidentally of the trajectories) and A_S is the amplitude of the streamlines. It is also required that the isotherms and streamlines, which are sinusoidal, must be either in phase or 180° out of phase. In Figure 1 the first three diagrams give three examples of such waves: retrograde waves, waves moving with speeds less, and waves moving with speeds greater than the zonal wind speed U . In case the isotherms and streamlines coincide, the wave is stationary ($c = 0$, not shown). The fourth diagram in the figure shows a pattern in which the isotherms and streamlines are 90° out of phase. In this case the amplitude ratio analysis breaks down, but a slightly different mathematical development leads to the result that the amplitude of the isotherms will constantly increase and that the wave moves with the same speed as the west wind U .

The reasons for the mathematical results can be seen qualitatively from the following considerations. Taking first the stationary wave, since

⁴C.-G. Rossby, Kinematic and Hydrostatic Properties of Certain Long Waves in the Westerlies ("Institute of Meteorology, University of Chicago, Miscellaneous Reports," No. 5 [Chicago, 1942]).

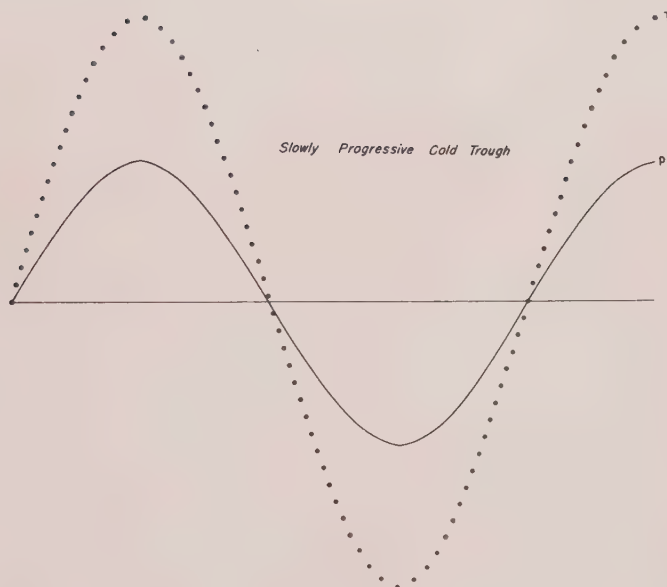
$$U > 0 > c$$

$$0 < \frac{A_T}{A_P} < 1$$



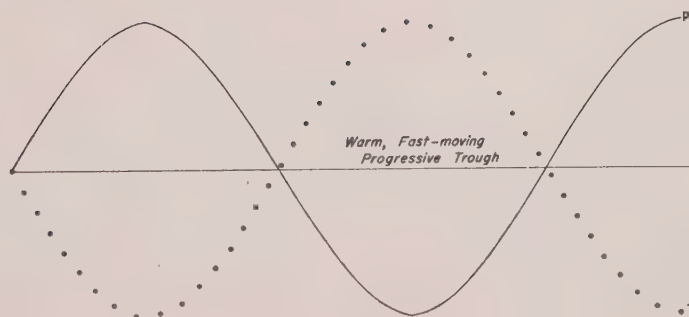
$$U > c > 0$$

$$\frac{A_T}{A_P} > 1$$



$$c > U > 0$$

$$\frac{A_T}{A_P} < 0$$



*Unstable Trough Moving With
the Speed of the Prevailing
West Wind ———*

$$c = U > 0$$

A_T increases
with time

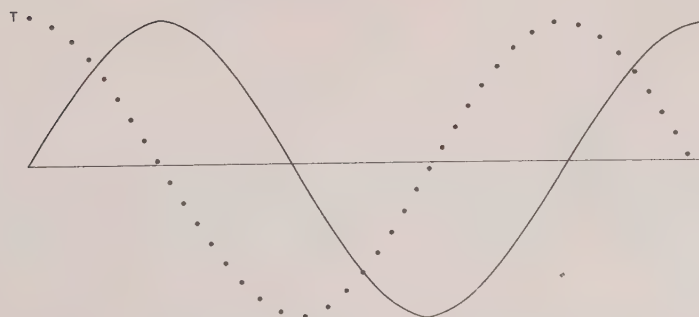


FIG. 1.—Isobar-isotherm patterns in unchanging waves (after Rossby).

the isotherms and streamlines are parallel at any given point in a coordinate system fixed on the streamlines, the air arriving is always of the same temperature as that just leaving, so that the wave does not need to move in order to maintain its form. In the retrograde trough, however, if the wave did not move westward, the northwest winds behind the trough, for example, would carry too low temperatures southward with respect to the streamlines; the wave, in moving westward, both shifts a cooler portion of the pattern toward the northwest wind and turns that wind sooner into west and southwest so that it does not reach such southerly latitudes. Conversely in the case of the slowly progressive trough, the northwest winds would move too high temperatures up to the trough line were the wave not to move eastward, shifting the cooler portion of the isotherm pattern ahead of the northwest winds and at the same time sending them farther south than otherwise before they turn into west winds. (The language used above should not be construed as implying particular causal relations between the winds, troughs, and isotherms, since the results are a purely formal consequence of the assumptions, particularly that of no change of shape.)

The trajectories of individual particles in these wave forms have certain regular relations to the troughs and ridges. In the cases of the retrograde, the slowly progressive, and the stationary waves the trajectory will have a sinusoidal course along which the particle proceeds through the streamline pattern from west to east. Thus a southwest wind starting ahead of a trough will, when it has later turned into northwest, be located on the forward side of the same ridge behind which it was located at the beginning. With the warm, out-of-phase trough this same southwest wind, when it has turned into northwest, will be located behind the trough ahead of which it started; while for the 90° out-of-phase trough the relative positions of trough and particle will not change, so that the particle starting as a southwest wind will remain southwest and its path will be a straight line out toward the northeast.

Rossby has carried out a further analysis in which the vorticity changes necessary to produce these sinusoidal paths in a west-wind belt with the above sine-wave streamline distribution are considered to be due to latitude changes alone without any convergence or divergence (see discussion of the vorticity theorem below).⁵ This study leads to the result

⁵C.-G. Rossby, "Relation between Variations in the Intensity of the Zonal Circulation of the Atmosphere and the Displacements of the Semi-permanent Centers of Action," Journal of Marine Research (Sears Foundation), Vol. II, No. 1 (1939).

that

$$c = U - \frac{\beta L^2}{4\pi^2} \quad (4)$$

where β is the rate of variation of the Coriolis parameter f in the south-north direction. Table 1 gives values of the quantity $\beta L^2/4\pi^2$ in units of degrees of latitude per day at various latitudes in terms of L , the wave length, measured in degrees of latitude.⁶

TABLE 1

Lat	$\beta L^2/4\pi^2$ in deg lat/day
75	$1.45 \times 10^{-3} L^2$
60	2.79
45	3.95
30	4.83
15	5.39
0	5.59

The constants in this table are such that for the ordinary small daily troughs with wave lengths of 10° to 20° or less the term $\beta L^2/4\pi^2$ is only of the order of 1° lat/day, and consequently, according to equation (4), the waves should move with just about the velocity of the west wind or slightly less. This as a matter of fact is the case with a great many of the small daily troughs on the 10,000-foot chart.⁷

3. Constant Absolute Vorticity (C.A.V.) Trajectories⁸

The basic idea underlying the whole project has been, instead of basing the forecast picture solely on sets of instantaneous streamlines as exemplified in our kinematic patterns above, to use the trajectories of air

⁶Degrees of latitude will be used hereafter for most measurements of distance since it is a unit so easy to pick off from the latitude-longitude grid on the majority of meteorological charts. Also it is convenient in a velocity unit for conversion from mi/hr, since

$1^\circ \text{ lat/day} = 2.9 \text{ mi/hr} \approx 3 \text{ mi/hr}.$

⁷See subsec. 5a in chap. III and discussions in the rest of sec. 5.

⁸In referring to the trajectories, the abbreviation will be used, since the full name is rather cumbersome. Notice later that, because of the no-shear assumption, these are not the only possible paths having constant absolute vorticity.

streams or particles as another control and indication of the streamline pattern to be expected at some future time. By making a set of simplifying assumptions, it is possible to compute directly paths for streams having certain characteristics and thus to introduce a more or less mechanical control of some of the forecast possibilities and reduce somewhat the purely personal element. The assumptions are of two kinds: those which merely restrict the types of currents to which the technique can be applied and those which leave out of account processes which are actually operating. A description of the development will make clear what some of these are.

First, for an atmosphere consisting of a series of homogeneous layers moving without friction or individual change in density, the equations of motion and continuity lead to a vorticity equation⁹ expressed thus

$$\frac{d}{dt} \left(\frac{f + \zeta}{\Delta} \right) = 0 \quad (5)$$

where f is the Coriolis parameter, ζ is the relative vorticity about a vertical axis with respect to the earth, and Δ is the depth of the particular layer under consideration expressed as the pressure difference between the top and bottom. If the depth is constant—in other words, if there is no convergence or divergence—the equation reduces to

$$\frac{d}{dt} (f + \zeta) = 0 \quad (6)$$

which, integrated with respect to time, gives a constant:

$$f + \zeta = k \quad (7)$$

This equation means that the absolute vorticity of a particular column—made up of f , the vorticity of the earth about the vertical, and ζ , the vorticity of the air relative to the earth—is constant under the specified conditions. Displacements north and south over the earth, therefore, will change the relative vorticity of an element of air, since the vorticity of the earth under it will change, while the sum of the two must remain constant. As an element moves north in the northern hemisphere under the above conditions, the earth under it at successive positions will have an increased cyclonic component of rotation about the vertical. This will reduce the cyclonic relative vorticity of the element or increase its anticyclonic vorticity, while the reverse will occur for displacement southward.

⁹B. Haurwitz, Dynamic Meteorology (New York: McGraw-Hill Book Co., 1941), pp. 233-35; C.-G. Rossby, "Planetary Flow Patterns in the Atmosphere," Quart. Jour. Royal Met. Soc., Vol. LXVI, Suppl. 68 (1940).

Consider now a portion of a streamline of horizontal air motion. It can be shown that the vorticity about a vertical axis is

$$\zeta = \frac{c}{R_s} + \frac{\partial c}{\partial n} \quad (8)$$

where c is the velocity at the point, R_s is the radius of curvature of the streamline there, and $\partial c / \partial n$ is the rate of change of the velocity along the normal to the streamline. Also it is true that

$$\frac{c}{R_T} = \frac{c}{R_s} + \frac{\partial \psi}{\partial t} \quad (9)$$

where R_T is the radius of curvature of the trajectory passing through the point at a given time and ψ is the angle between the tangent to the streamline at that point and some fixed direction.¹⁰ The term $\partial \psi / \partial t$ thus expresses the instantaneous rate at which the streamline through the point is rotating. In equations (8) and (9), R_T , R_s , and n are measured from the center of curvature and counted positive from left to right when facing downstream. If we now substitute the value of c/R_s from equation (9) into equation (8), we obtain that

$$\zeta = \frac{c}{R_T} + \frac{\partial c}{\partial n} - \frac{\partial \psi}{\partial t} \quad (10)$$

The term $\partial c / \partial n$ is eliminated, first, by restricting consideration to currents where it is initially zero and, second, by assuming that for such a current it will remain zero. The term $\partial \psi / \partial t$ is just neglected. There is no particularly cogent a priori reason for these two last steps, except that so far there is no practicable way of handling the terms mathematically, and their justification, if any, will have to come mainly from experience; from seeing in how far the results of our computations are verified on the maps. (However, see end of this section.)

The final result of these steps is that

$$\zeta = \frac{c}{R_T} \quad (11)$$

This, when substituted in the reduced vorticity equation, gives

$$f + \frac{c}{R_T} = h \quad (12)$$

¹⁰J. Blaton, "Zur Kinematik nichtstationärer Luftströmungen," Bull. Soc. Geophys. Varsovie (1938).

Now let us choose a right-handed Cartesian coordinate system with the positive x-axis pointing eastward and the y-axis northward and with the origin on the latitude for which the relative vorticity of the particle to be computed is zero. Then at $y = 0$, c/R_T will be zero, and, letting $f = f_0$ at $y = 0$, we find from equation (12) that $f_0 = k$. Consequently,

$$f + \frac{c}{R_T} = f_0 \quad \text{or} \quad (f - f_0) + \frac{c}{R_T} = 0. \quad (13)$$

Now to a first approximation

$$(f - f_0) = \beta y \quad (14)$$

where β is the rate of variation of f in the y direction and is assumed to be constant over the range of latitude of the path. Actually β is a cosine function of the latitude, but the error thus introduced is not great except possibly in high latitudes.¹¹ The final result is

$$\frac{c}{R_T} = -\beta y. \quad (15)$$

The next step is to introduce the explicit expression for the radius of curvature

$$\frac{1}{R_T} = \frac{y''}{(1 + y'^2)^{3/2}} \quad (16)$$

(y' and y'' are the first and second derivatives, respectively, of y with respect to x), obtaining

$$\frac{c y''}{(1 + y'^2)^{3/2}} = -\beta y. \quad (17)$$

The final assumption, which transforms this to a second-order differential equation with constant coefficients, is that c remains constant along the path. This is equivalent to specifying no friction and a pressure

¹¹An analysis carried out by Mr. George Platzman at the University of Chicago using the complete equations of motion on a spherical earth and integrating them for a constant normal pressure force (see end of this section) indicates that the difference between the paths on the earth and those computed on the plane system of coordinates which is used above is of the following general kind for westerly winds. The northern branch of the path is smaller both in amplitude and in length, and the southern branch is larger on the earth than in the plane system. For a due-west wind the path runs along the parallel of latitude in the plane case, while on the sphere it starts out along a great-circle path, dips below the parallel, and then comes back up and just touches it at a point of tangency. The magnitude of this dip for middle latitudes and ordinary velocities is of the order of 2° or 3° lat (see note on p. 30).

gradient which is always normal to the instantaneous velocity of the particle. The differential equation can now be integrated by a change of variables and a number of other devices which yield the following equations:

$$y_m = h\sqrt{2} \sin \frac{1}{2} \phi_i \quad (18)$$

$$D = \frac{h}{\sqrt{2}} \left(2 \int_0^{\pi/2} \frac{1}{\sqrt{1 - \sin^2 \frac{1}{2} \phi_i \sin^2 q}} dq - \int_0^{\pi/2} \frac{dq}{\sqrt{1 - \sin^2 \frac{1}{2} \phi_i \sin^2 q}} \right) \quad (19)$$

$$T = \frac{h}{c\sqrt{2}} \int_0^{\pi/2} \frac{dq}{\sqrt{1 - \sin^2 \frac{1}{2} \phi_i \sin^2 q}}, \quad (20)$$

where $h = \sqrt{2c/\beta}$, q is the variable of integration in the complete elliptic integrals and is such that $\cos q = y/y_m$, c is the speed of the particle, $\beta = \partial f / \partial y = (2\Omega \cos \phi) / R$, Ω is the angular velocity of the earth, ϕ is the latitude, and R is the radius of the earth.

ϕ_i is the angle measured from east at which the current intersects the latitude line, where its relative vorticity is zero. This latitude is called the inflection latitude, since there the relative vorticity changes from cyclonic to anticyclonic or vice versa, and the vorticity by the assumptions is expressed only as curvature of the path.

The three quantities y_m , D , and T are dimensions of the C.A.V. paths from which, when determined in each particular case, the path may be plotted and sketched on a base map. y_m is the amplitude, the distance north-south in degrees of latitude from the inflection point to the maximum northerly or southerly position on the path. D is the quarter wave length, the east-west distance in degrees of longitude from an inflection point to a maximum point or vice versa. T is the quarter period, the time required to traverse the curve between two adjacent defining points. A fourth quantity, y_1 , is used when ϕ_i is greater than 90° and is the distance above or below the inflection point in degrees of latitude at which the wind becomes due south or north, respectively. Its value is

$$y_1 = h \sqrt{\sin(\phi_i - \frac{\pi}{2})} \quad (21)$$

and it is useful chiefly in sketching properly the C.A.V. paths for easterly winds.

Equations (18), (19), and (20) show that the dimensions of the C.A.V. paths depend upon c , ϕ_i , and the inflection latitude, since β is to be evaluated at the inflection latitude. These three quantities are the ones usually measured from the map for each current (see chap. II for details).

OM' station	model	T	T	OM' temperature
		ΔT	P	OM' pressure
		ΔP	ΔP	24 hour change in P
			ΔT	24 hour change in T

T	10M' temperature
P	10M' pressure
Δp	24 hour change in
ΔT	24 hour change in

10M' isobars for 5mb. intervals (written 5 instead of 705)

7 Intermediate 10M' isobars

+10 Mean isotherms - sea level to 10M'

Dissipating trough

Trajectories of centers

4c Initial positions of selected winds at 10M' $\left(\begin{array}{cc} c, \text{ cyclonic} & e, \text{ doubtful} \\ a, \text{ anticyclonic} & d, \text{ doubtful} \end{array} \right)$

— · 10M' isallobars

Cold frontogenesis

WIND CHECK SHEET FORM

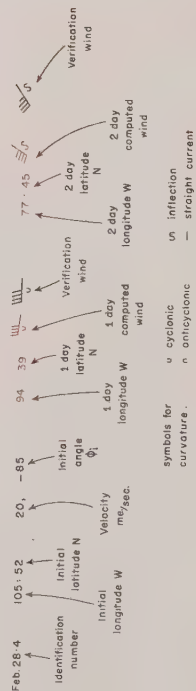


FIGURE 2a

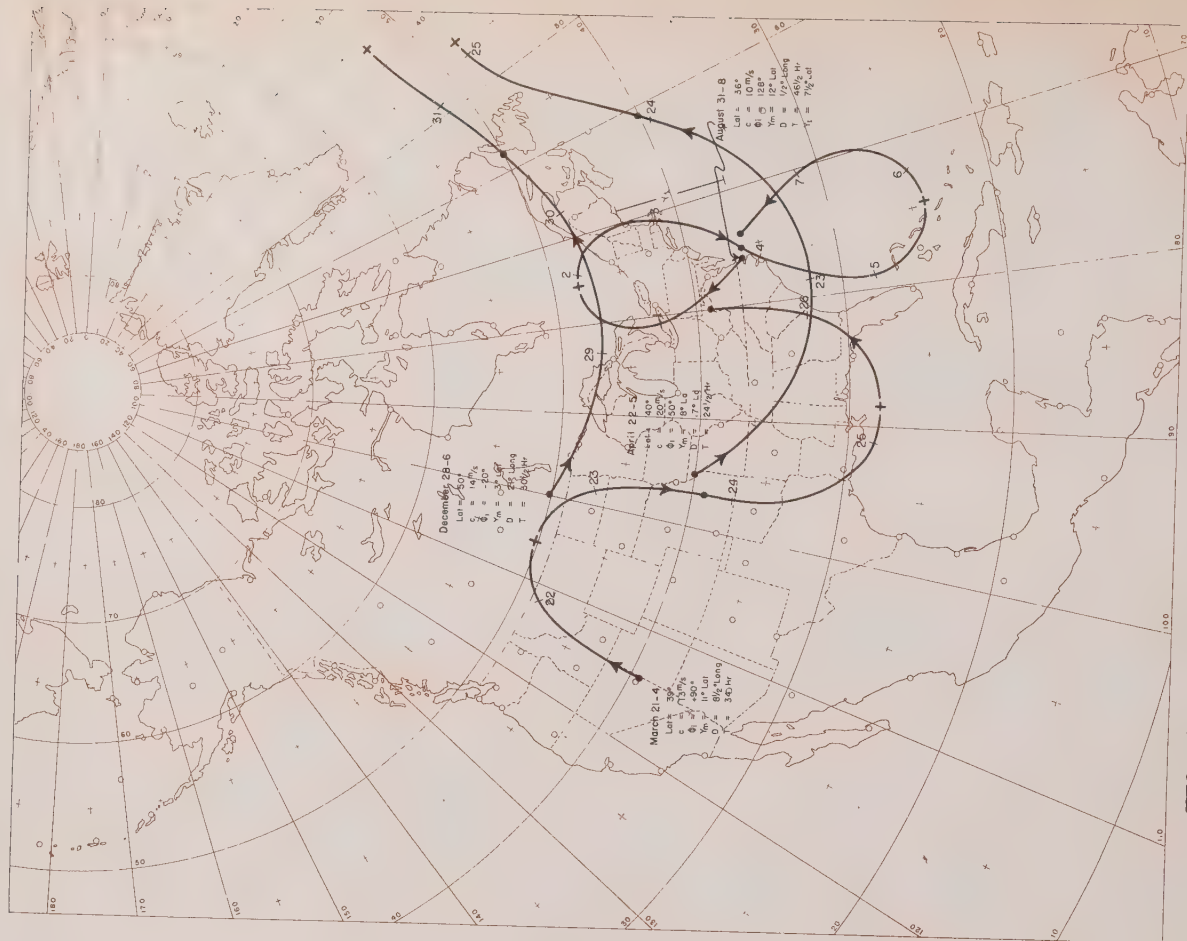


FIG. 2b.---Sample C.A.V. trajectories. (Strokes and numerals along the paths mark positions and dates for 24-hour intervals from the starting-point on the 2300 EST map of the initial date.)

At least for the velocity factor it is evident from the equations that the stronger the velocity, the larger the dimensions of the C.A.V. path and the less the value of the quarter period. The dependence on ϕ_1 is such that the smaller this angle, the flatter and more elongated is the character of the path. In Figure 2b are given a number of typical paths. Let us consider the particle Dec. 28-6, which, starting with a rather small initial angle toward the south, picks up cyclonic relative vorticity or curvature as it moves southward, reaches a point where it is a west wind and is turning cyclonically at a maximum rate, and when it has returned to the inflection latitude is again traveling in a straight line with respect to the earth. As it crosses north of the inflection latitude, it begins to pick up anti-cyclonic curvature and turns back toward the inflection latitude, the whole pattern being rather flat and resembling a sine wave. If the initial angle is larger, as for Mar. 21-4, the path goes farther north and south and begins to be compressed in the east-west direction. For still larger values of ϕ_1 the path becomes a figure-eight, like that of Aug. 31-8, and for angles greater than 130° from east the inflection points on the curve progress westward, and the particle goes around a closed loop on the upper and lower branches of the curve.

The positions of each particle have been marked on these paths at 24-hour intervals by interpolation using the values of the time at the defining points as determined by the quarter period. To use the trajectories of a set of these particles (at the 10,000-foot level) for the purpose of drawing a 10,000-foot prognostic chart, we enter from the C.A.V. paths at the correct positions all the winds which belong to the particular time of the desired chart. This collection, if sufficiently dense, will give a fair idea of a streamline pattern on which to base the forecast of the isobars.

Figures 3-8 give two situations in which the trajectories gave a good indication of the future course of events. Figures 3-7 are a series of 10,000-foot maps over the United States at 2300 EST from Oct. 17 to 21, 1942. They show a sequence of events which may be described in this way: when a strong upper flow from the southwest appears off the West Coast of the United States in the Gulf of Alaska, there is a distinct tendency for it to appear two days or so later over the Middle West as a northwest current with a trough aloft in the Mississippi Valley. This development will be particularly active in inducing strong pressure falls in the trough if it occurs near or in the cold seasons when around and west of the Hudson Bay region there is a good supply of Pc air with low mean temperatures between 10,000 feet and the surface available for an outbreak southward. (Hereafter,

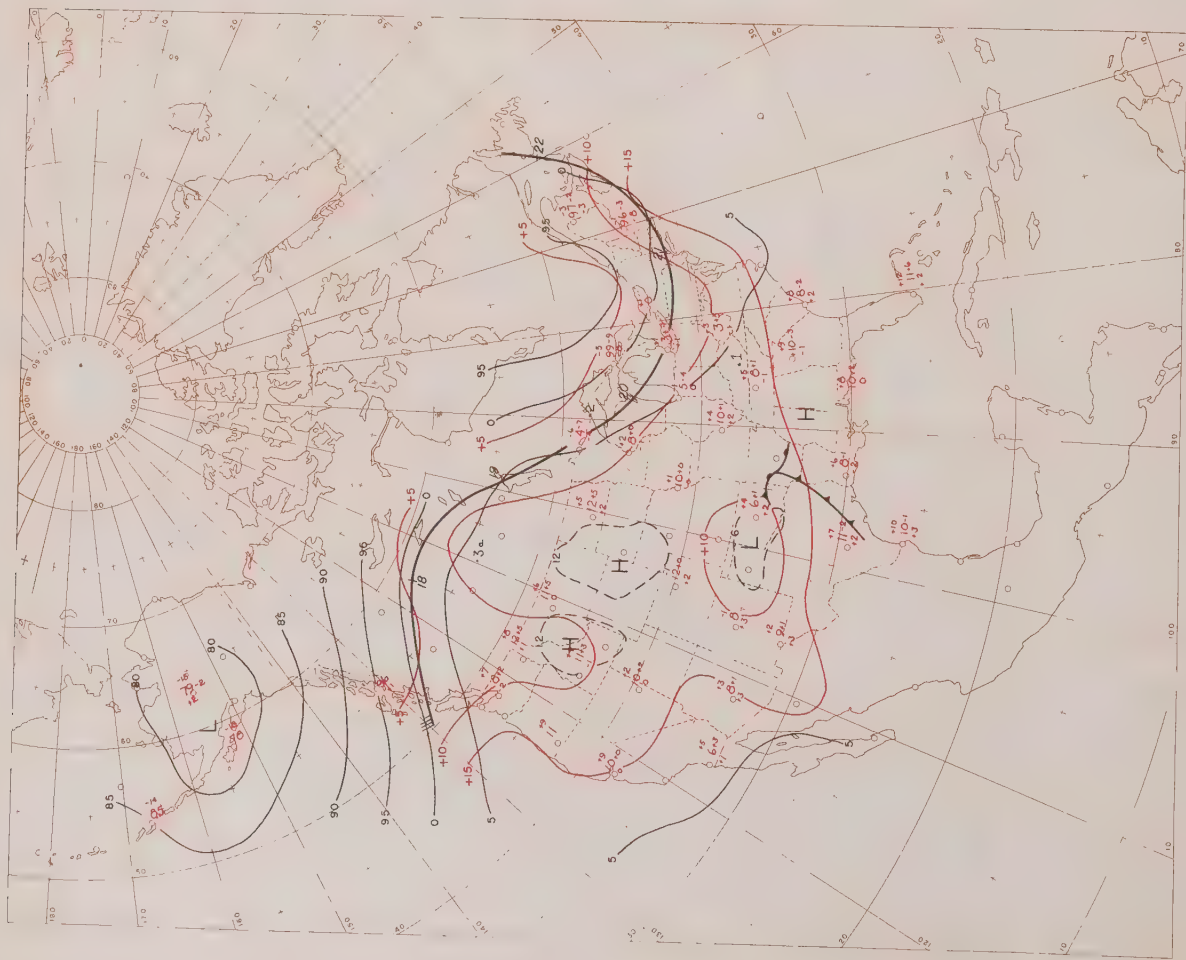


FIG. 3.—Series with plotted C.A.V. trajectory of a Southwest Gulf of Alaska wind. 10,000-foot map for October 17, 1942, 2300 EST.

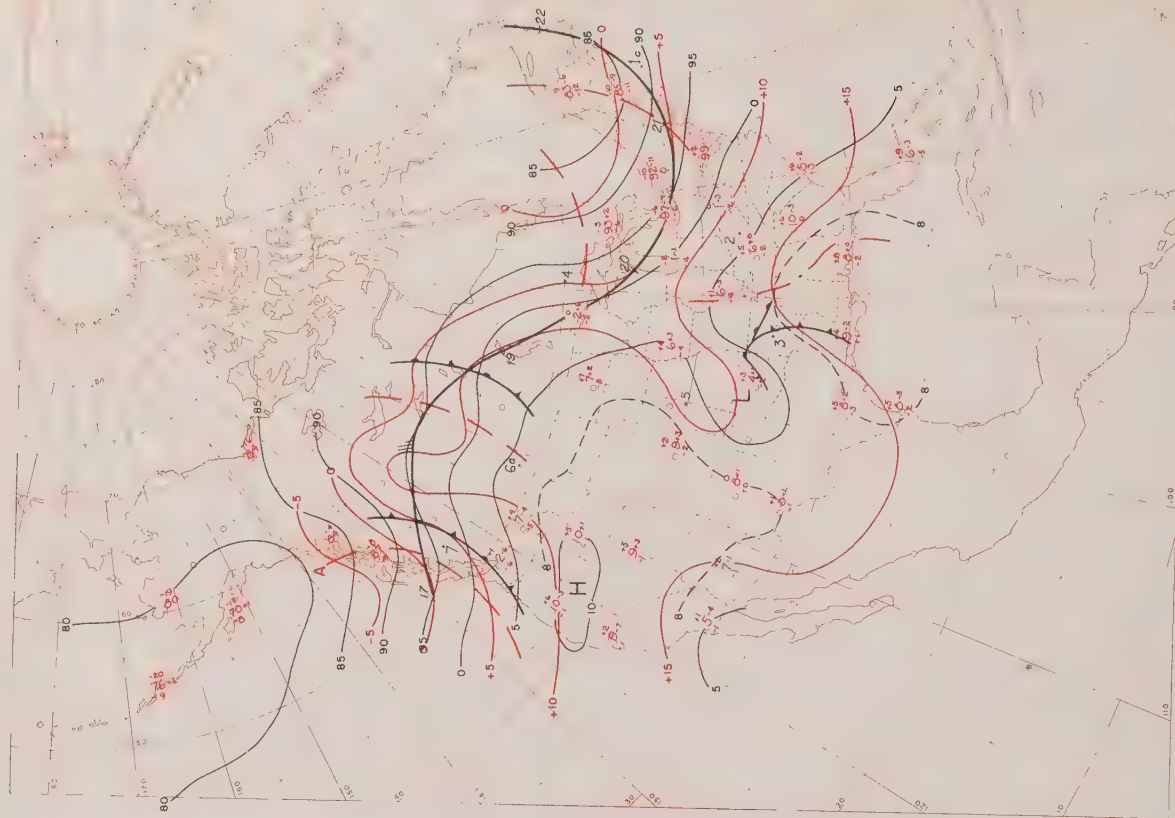


FIG. 4.—Series with plotted C.A.V. trajectory of a Southwest Gulf of Alaska wind. 10,000-foot map for October 18, 1942, 2300 EST.

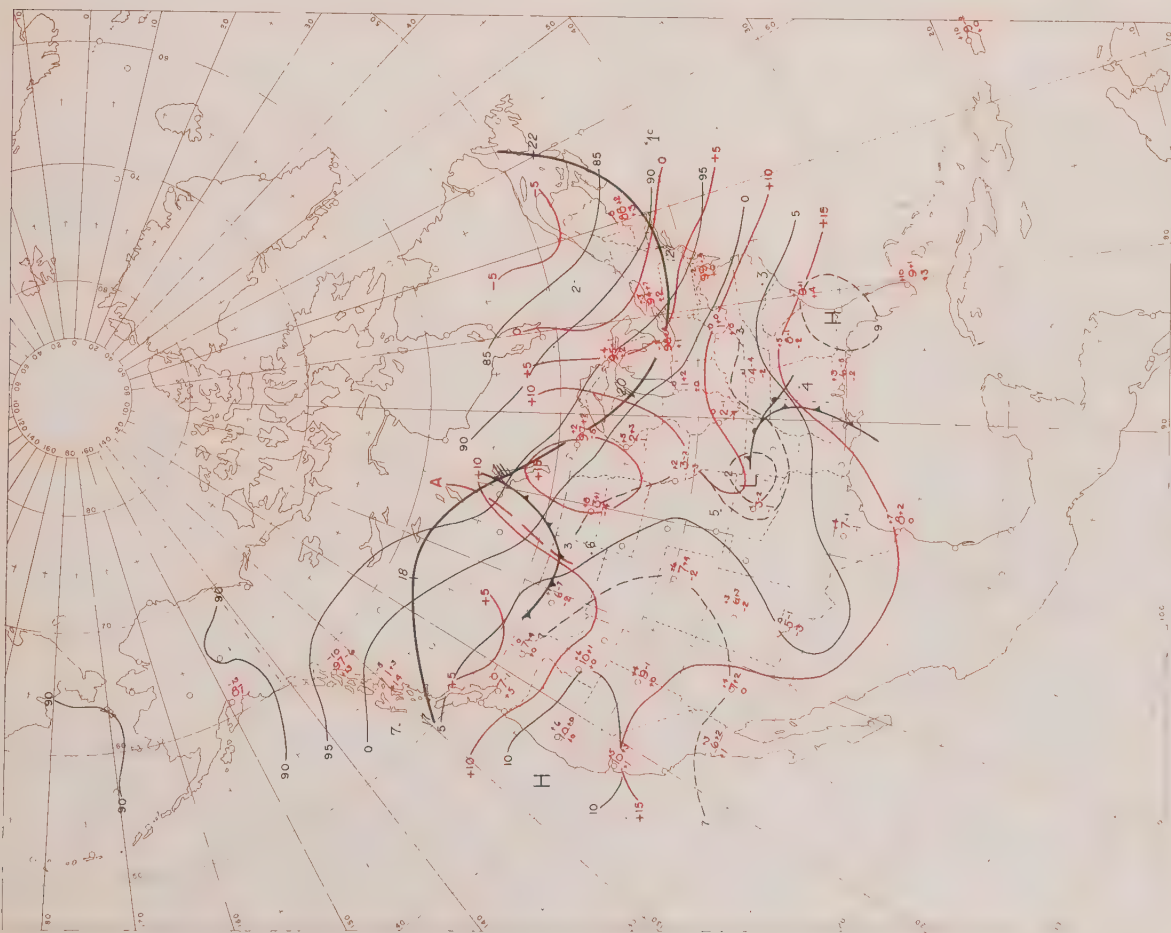


FIG. 5.—Series with plotted C.A.V. trajectory of a Southwest Gulf of Alaska wind. 10,000-foot map for October 19, 1942, 2300 EST.

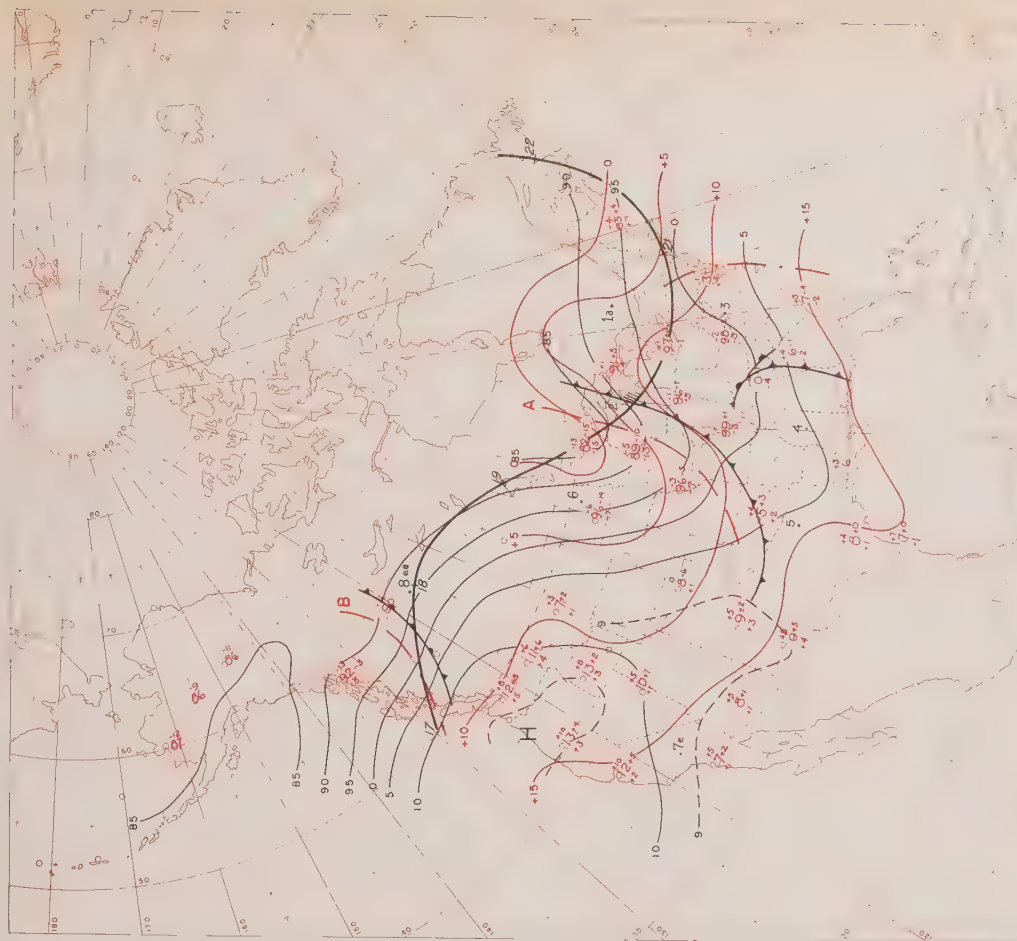


FIG. 6.—Series with plotted C.A.V. trajectory of a Southwest Gulf of Alaska wind. 10,000-foot map for October 20, 1942, 2300 EST.

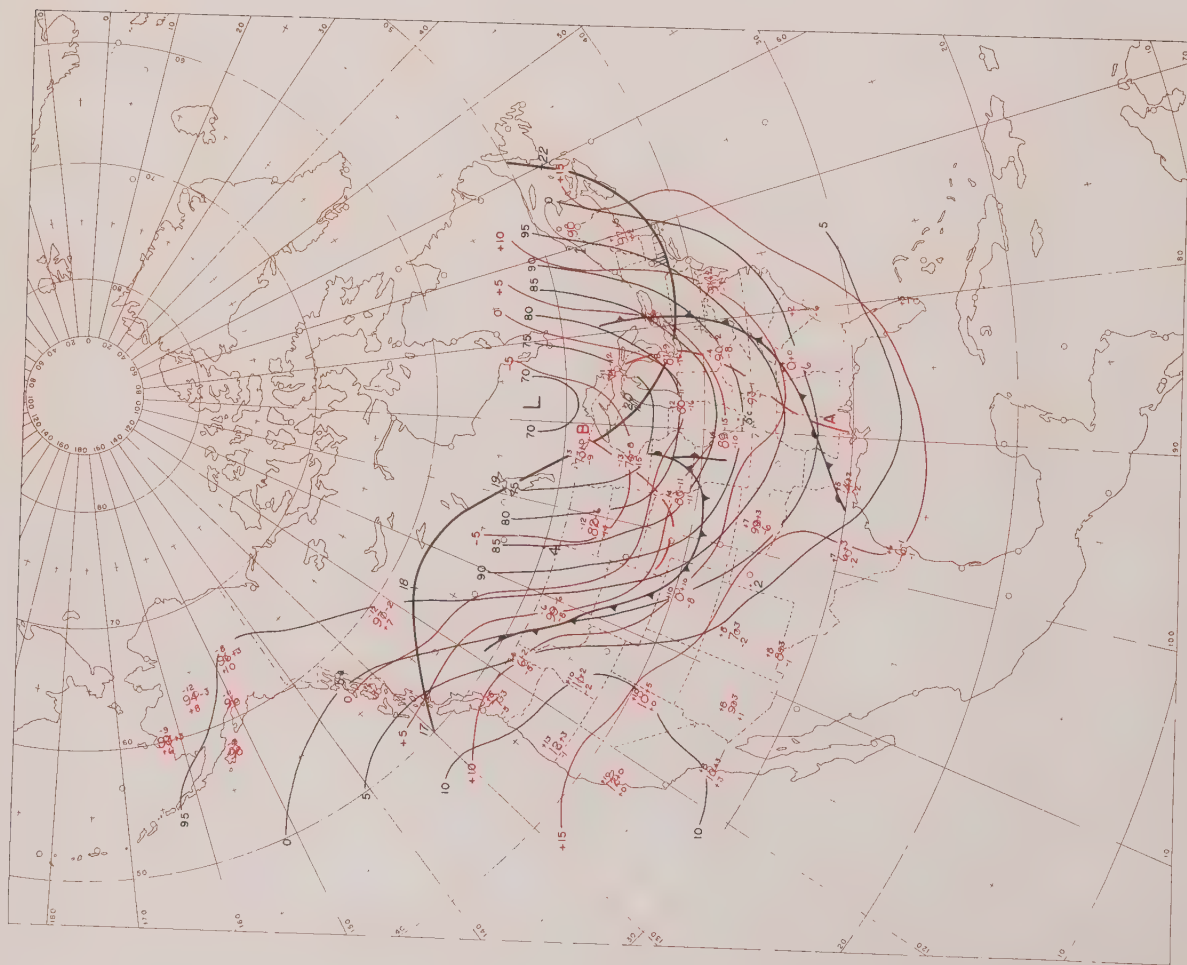


FIG. 7.—Series with plotted C.A.V. trajectory of a Southwest Gulf of Alaska wind. 10,000-foot map for October 21, 1942, 2300 EST.

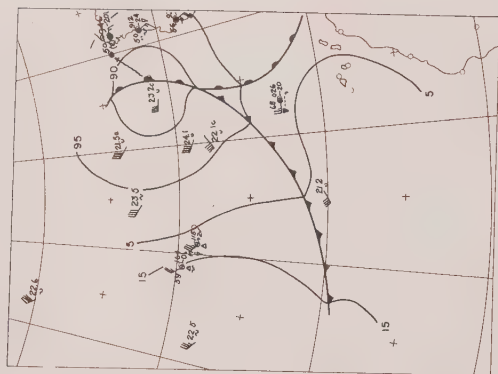


FIG. 8a.—Deep cyclone between Portugal and the Azores Islands with 10,000-foot computed winds. Surface map for October 28, 1942, 0130 EST.

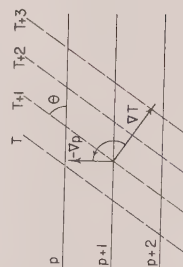


FIGURE 8b

unless otherwise indicated, mean temperature will refer to the mean virtual temperature determined by the sea-level and 10,000-foot pressures.) The map for the 17th is not very clear in indicating a trough deepening west of the Lakes: there is a strong northerly flow over the Lakes which the next day did deepen the trough there considerably, but it is well to the east, and the upper high over the mountains might, as sometimes happens, drift eastward giving warm anticyclonic weather over most of the United States. There are at least three indications on the 10,000-foot map that this will not occur: one is the strong southwesterly flow in the Gulf of Alaska, another is the cyclonic circulation in Oklahoma which if vigorous enough would tend to keep things broken down to the east with cold air getting an impulse southward over the Plains, and a third is the frequent tendency, once a cold northwesterly flow is established in the east, for the trough ahead to retrogress with minor troughs bringing down cold air to the rear until the flow is established clear back to the mountains. This last process is accompanied by the retreat of the upper high, if there is one, off the West Coast, as occurs in the case at hand. Note carefully on succeeding maps the sequence of events and the relation of the trajectory to the main deepening trough (surface events may be inferred from the fronts which have been plotted on the maps and from the relation of the 10,000-foot isobars to the mean isotherms). Three further points are of particular interest in the series. First, the initial trough from the West Coast disappears when it reaches the northwest flow in the east on the 19th. Quite often it happens that the first trough of a series coming in on the West Coast will weaken or even die out, while later members take over the active developments. Second, the Oklahoma circulation unites with the main trough in a characteristic manner. This sort of process has occurred in many of the cases of strong deepening during this series; that is, a more or less lagging and mildly active trough or cyclonic circulation has, when overtaken by an active trough, united with it, accompanied by pronounced deepening effects. Third, the relation of the trajectory to the trough on the 20th and 21st is an example of a deviation from the computed winds which occurs in these cases of strong deepening. What is evidently partly convergence ahead of the trough produces strong southwest currents not indicated or indicated only weakly by the trajectory winds.¹²

Figure 8a gives the surface map and computed 10,000-foot winds between Spain and the Azores on Oct. 27, 1942, at 2300 EST, 6 days after the

¹²See examples in sec. 1 of chap. III.

large mean trough over the Great Lakes had established itself on our map for the 21st and from which many of these computed winds originally started. On the 21st a surface high of at least 1029 mb was situated just north of the Iberian Peninsula in what is a fairly stable position for the high. The low on the midnight map of the 27th was the first main development in the ocean in this far-south position following the high (at least one previous low seems to have moved southeastward over France or Spain on about the 25th). The 10,000-foot computed winds give a very strong suggestion of the pattern which would be expected above a deep low of this type. In addition, it is perhaps significant that none of these winds appeared in the area north of 45° latitude above the low. This would suggest the possibility of a closed low at 10,000 feet, since, from the nature of most of the C.A.V. trajectory patterns, westerlies are indicated as a rule and easterly circulations mainly by default if at all. In passing it may be mentioned that the surface analysis shown here, while based on scanty reports from only land stations around the area, is fairly certain, since well-marked frontal passages occurred at the Azores the day before and at the Portuguese and Madeira stations on the day following this map.

The two examples above, and a number of others which could be given, show at times a remarkable degree of verification of the computed winds; a few have verified very closely for 6 days. However, experience has shown a number of influences to be operating, as indeed should be expected from the nature of the assumptions, which cause major difficulties for the forecaster trying to evaluate their relative importance in a particular case. They will be discussed at length in chapter III, particularly in section 1, mainly on an empirical basis. Here we shall take up theoretically the deviations to be expected from various factors under certain assumed conditions.

The complete expression for c/R_T at any time t in terms of conditions at $t = 0$ and $t = t$ as derived from Bjerknes' Circulation Theorem without any of the approximations it has been necessary to introduce above, except for the neglect of transport of horizontal components of vorticity into the vertical, is

$$\frac{c}{R_T} = \zeta_0 + (f_0 - f) + (f_0 + \zeta_0) \frac{\Delta - \Delta_0}{\Delta_0} + \frac{\partial \psi}{\partial t} - \frac{\partial c}{\partial n} + \int_0^t N dt + \begin{matrix} \text{fric-} \\ \text{tion} \\ \text{term} \end{matrix} \quad (22)$$

In this equation N is the number of horizontal solenoids per unit area, and the quantities c/R_T , f , Δ , $\frac{\partial \psi}{\partial t}$, and $\frac{\partial c}{\partial n}$ are to be measured at the time t for the individual column of air while quantities with subscript 0 are to be measured at the time zero. The solenoid term and the friction term are of the nature of integrals of the time rate of change of the vorticity

with respect to the time.

The left-hand term and the first two terms on the right in equation (22) are the terms which are used in computing the C.A.V. paths. Let us now consider separately the effect of each of the terms upon deviations from the C.A.V. path. First the term c/R_T , though used to compute the paths, contains the possibility of deviations, since c was assumed to be a constant. If acceleration occurs through some means which does not change the vorticity, the path actually observed will deviate from the original C.A.V. path in the direction in which the C.A.V. path for the new velocity deviates from the original. If the speed increases, the path for a northwest wind will go farther south and farther east than the originally computed path before turning into a west wind, while if the speed decreases it will do so sooner.

The next term, $(f_0 + \zeta_0) \frac{\Delta - \Delta_0}{\Delta_0}$, is the convergence term. Since the absolute vorticity $f_0 + \zeta_0$ is positive in all cases in the northern hemisphere, except possibly at times near the equator and in certain small-scale circulations, convergence producing an increase of Δ will make $\frac{\Delta - \Delta_0}{\Delta_0}$ positive and, the whole term, then being positive, will make a positive or cyclonic contribution to c/R_T . This will mean that the northwest current, for instance, will turn cyclonically more than called for by the change in latitude, i.e., more cyclonically than the C.A.V. path. On the other hand, if divergence occurs, the term $\frac{\Delta - \Delta_0}{\Delta_0}$ is negative, and the effect will be a negative or anticyclonic contribution to c/R_T . With divergence the northwest wind will go farther south than the C.A.V. path on a track which is either merely less cyclonic than that path, straight, or actually curved anticyclonically.¹³ As a matter of fact, the average type

¹³A relation which gives an immediate estimate of the amount of divergence or convergence which has taken place in certain types of currents can be obtained from the form of the vorticity equation which states that $\frac{f + \zeta}{\Delta} = \frac{f_0 + \zeta_0}{\Delta_0}$ (cf. eq. [5]). If we re-write this in the form $\frac{\Delta}{\Delta_0} = \frac{f + \zeta}{f_0 + \zeta_0}$ and consider a ratio of the Δ 's such that $\frac{\Delta}{\Delta_0} = f/f_0 = \frac{f + \zeta}{f_0 + \zeta_0}$, then by an elementary theorem of ratios, we find that $f/f_0 = \zeta/\zeta_0$. In the particular case in which ζ_0 equals 0, ζ also will equal 0. Thus, if we observe a straight current with no shear proceeding from south to north and continuing to move straight without picking up anticyclonic vorticity, we can say that the depth of any particular column in the current should increase proportionally as f at successive latitudes or, since the factor 2Ω drops out of the ratio of the f 's, proportionally as the sine of the latitude. A column moving in this manner from latitude 30 to latitude 45 should increase in depth by the factor $\frac{\sin 45}{\sin 30} \approx 1.4$ (see p. 48).

of deviation of 10,000-foot currents from the C.A.V. paths is such as could be caused by divergence in the northwest winds and convergence in the southwest winds (see chap. III).

The term $\frac{\partial \psi}{\partial \tau}$, the instantaneous rate of rotation of the streamlines, is easy to determine at the initial instant, but, as for the divergence, it is hard to see any means of evaluating it for later times when it is really needed. The effect is straightforward; veering of the wind at a given point is associated with a path more anticyclonic than the C.A.V. path and backing with a more cyclonically curved trajectory. But, in trying to estimate the effect on the path of a particular fluid element, it must be remembered that $\frac{\partial \psi}{\partial \tau}$ must be evaluated only over a time interval which is sufficiently small to be considered infinitesimal, since, if this is not so, the fluid element will have moved so far away that it will be $\frac{\partial \psi}{\partial \tau}$ at some other position which is affecting it. For the inflection points $\frac{\partial \psi}{\partial \tau}$ will at the initial position normally be zero, since the wind is changing from backing as the ridge passes to veering as the trough approaches or vice versa, but that it should remain small along the path of a particle would require, for example, that the streamline pattern be slowly moving or that the troughs be relatively flat and of long wave length, or some more complicated condition. For purposes of comparison of f , ζ , and $\frac{\partial \psi}{\partial \tau}$ Table 2 gives the conversion of these quantities from practical units to sec^{-1} .

TABLE 2

Latitude	f	$\frac{\partial \psi}{\partial \tau}$
10	$.25 \times 10^{-4}$ rad/sec	$10^\circ/6 \text{ hr} = .08 \times 10^{-4}$ rad/sec
20	.50	20° .16
30	.73	30° .24
40	.94	40° .32
50	1.12	50° .40
60	1.26	60° .48
70	1.37	70° .57
80	1.44	80° .65
90	1.46	90° .73

For ζ expressed as curvature, ζ in rad/sec = 0.0402×10^{-4} c/R , where c is in mi/hr and R is in degrees latitude.

The term $\frac{\partial c}{\partial n}$ is another for which it is hard to see any way of evaluation beforehand, but particularly for broad and extensive currents it is likely to be a comparatively minor aberration. Since this term enters into the equation with a minus sign, the development of cyclonic shear in the fluid element will produce a deviation from the C.A.V. path in the direction of anticyclonic curvature and vice versa. If, as we shall later

do, it is desired to draw some tentative conclusions about the existence of convergence or divergence in certain currents from observed deviations from C.A.V. paths, it will be necessary, for one thing, to check along the observed path and see that considerable amounts of shear have not developed. (If one wishes to compare the magnitude of shear with the curvature, note that when the shear is measured as change of speed in mi/hr per degree of latitude across the current, the units are the same as when the vorticity due to curvature is determined from the speed in mi/hr and the radius of curvature in degrees of latitude.)

The solenoid term in equation (22) can be evaluated from the expression

$$N = \frac{R}{mp} \left[\frac{\partial T}{\partial x} \frac{\partial p}{\partial y} - \frac{\partial T}{\partial y} \frac{\partial p}{\partial x} \right], \quad (23)$$

where R/m is the gas constant for air and equals 2.87×10^6 ergs/gm per deg, and p is the pressure, provided the variation of N with time is known for the fluid element. This again is not tractable in general, but from a simple and extreme case we can at least get an idea of the possible magnitude of horizontal solenoid effects. Suppose we have a set of east-west isobars at 10,000 feet such that $\frac{\partial p}{\partial y} = -3$ mb/100 km and a set of south-north isotherms such that $\frac{\partial T}{\partial x} = 2^\circ$ C/100 km, the other two space derivatives being zero. This will correspond to a cyclonic acceleration of vorticity for the northern hemisphere. Both of these gradient values are quite high, and choosing the isolines at right angles gives a maximum value to the term. Though it is probably not physically likely, let us assume that the strength of the solenoids remains unchanged over 24 hours; then for a pressure of 700 mb the acceleration of the vorticity due to the solenoids will be $2.46 \times 10^{-10} \text{ sec}^{-2}$, which over 24 hours would produce a vorticity change equal to $2.13 \times 10^{-5} \text{ sec}^{-1}$. If we start with a straight current and suppose that this vorticity is expressed as curvature, it would correspond for a 20 m/sec wind to a cyclonic radius of curvature of 940 km or approximately 9° of latitude. This is quite a short radius of curvature, so that the conclusion would tend to be that quite appreciable effects of the horizontal solenoid term are possible and might be expected to be observed, say, when strong releases of potential energy occur in deepening storms. Usually, of course, the gradients will be less and the isobars and isotherms not at right angles, and, in fact, in practice quite often the deviation from C.A.V. paths is opposite in sign even to that given by the solenoids, so that it is obvious that other factors are overbalancing the solenoid influence. Equation (23) above can be converted to practical units easy to evaluate on the weather map giving the absolute value of

$$[N] = \frac{d\zeta}{dt} = 2.88 \times 10^{-8} [\nabla p] [\nabla T] \sin \theta, \quad (24)$$

where θ is the smaller angle between the isotherms and isobars as in the diagram in Figure 8b, and the units are the following:

$$\frac{d\zeta}{dt} \text{ due to solenoids in sec}^{-1} \text{ per 6 hours}$$

$$\nabla p \text{ in mb per } 5^\circ \text{ of lat}$$

$$\nabla T \text{ in } ^\circ\text{C per } 5^\circ \text{ of lat}$$

Again p is 700 mb.

The friction term is the least amenable to theoretical discussion because of our relative ignorance of the exact form of frictional forces, but presumably this factor will include effects both of friction with the ground and of mixing between adjacent air streams. Some of the observed deviations can be traced to this source and occasionally can be anticipated qualitatively.

Finally, because it is usually neglected, though certain Japanese and German authors have thought it might be significant in some circumstances,¹⁴ we should mention the transport of horizontal components of vorticity into the vertical. If the complete equations of motion are cross-differentiated to obtain a complete vorticity equation for the vertical component, a term

$$\left[\frac{\partial w}{\partial y} \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \frac{\partial v}{\partial z} \right]$$

is found to enter into $\frac{d\zeta}{dt}$. In the first term here, for example, $\frac{\partial u}{\partial z}$ is a part of the expression for the vorticity component about the y -axis, and $\frac{\partial w}{\partial y}$ gives the rate at which vortex lines of the horizontal components are tilted, thus giving a component around the vertical axis. For a value of $\frac{\partial u}{\partial z}$ of 10 m/sec per 3 km and a value of $\frac{\partial w}{\partial y}$ of 1 cm/sec per 100 km, taking the other term equal to zero, this leads to a contribution to $\frac{d\zeta}{dt}$ equal to $3.3 \times 10^{-10} \text{ sec}^{-2}$. Thus for rather small values of the derivatives an effect of the same order as has been computed in the solenoid example is produced.

Some further discussion may help to clarify the physical meaning of the C.A.V. path implied by these numerous assumptions. Let us take equation (13)

$$f + \frac{c}{R_T} = f_0$$

and multiply through by c , obtaining

$$fc + \frac{c^2}{R_T} = f_0 c. \quad (25)$$

Since c is assumed constant and friction assumed to be absent, it follows

¹⁴Cf. S. Fujiwhara, "On the Mechanism of Extratropical Cyclones," Quart. Jour. Royal Met. Soc., XLIX (1923), 105.

that the pressure force is at all times normal to the direction of motion and, hence, that the motion is gradient. The equation of gradient motion is

$$fc + \frac{c^2}{R_T} = -\frac{1}{\rho} \frac{\partial p}{\partial n}, \quad (26)$$

the term on the right being the pressure force. Comparison of equations (25) and (26) shows that the pressure force is equal to $f_0 c$ and is therefore constant in magnitude. This implies that there is geostrophic balance at the inflection points and that the changes in curvature of the path arise from the variations of the Coriolis force due to changes in latitude.

At the equator the term $f_0 c$ becomes zero so that the C.A.V. path then coincides with the inertia path, since all forces not normal to the surface on which motion is taking place are zero except the Coriolis force. Also since $(f_0 + \zeta_0)$ is zero for a path with inflection point at the equator, convergence and divergence at least will no longer affect such a path (eq. [22]), and any deviations from the C.A.V. trajectory will have to be due to other factors.

CHAPTER II

PROCEDURE

The principal charts used in the work have been the 10,000-foot chart, the surface chart, and an advection chart of temperature for the layer between 10,000 feet and the surface. In addition to the plotted material shown on the 10,000-foot maps reproduced in this report, the mean temperature and the surface 24-hour pressure changes were plotted at a grid of points on the 10,000-foot chart, as were also the pilot-balloon velocities for 10,000 feet or its vicinity directly in mi/hr. Isolines were drawn on the 10,000-foot map for the pressure, the mean temperature, and the surface and 10,000-foot pressure changes, while troughs and ridge lines were drawn in colors which remained the same from day to day for each individual trough and ridge. It was found possible by varying the weights of the different lines, making the more important ones more prominent, to obtain a map which was relatively easy to read and possessed of the great advantage of presenting a great amount of pertinent data in a compact form.

The surface chart used was that drawn by the Chicago Weather Bureau District forecaster, but especial care was taken to keep it closely linked to the upper chart by plotting the surface fronts on the 10,000-foot map and by the mean temperature procedure.

The advection chart was prepared by estimating qualitatively the instantaneous temperature advection from the turning of the pilot-balloon winds between the surface and 10,000 feet¹ and plotting the 24-hour change in the mean temperature. Lines were drawn for the temperature change, and predominant warm- and cold-advection areas were shaded in lightly in red and blue.

In addition to these basic charts, a number of others were available and were consulted in so far as possible when occasion arose. A 10-km chart was drawn as part of the project, while charts of the height of the tropopause and of potential temperature and pressure at 13 km were drawn for a short time and were occasionally helpful. The Chicago Weather Bureau Office drew most of the other ordinary charts: winds-aloft charts for a number of levels, isentropic charts for two levels, and barometer charts of the 12-hour surface

¹E. H. Miller and W. L. Thompson, A Proposed Method for the Computation of the 10,000-Foot Tendency Field ("Institute of Meteorology, University of Chicago, Miscellaneous Reports," No. 1 [Chicago, 1942]).

pressure change. Several comments on the surface pressure changes will refer to this last chart.

The first step after the data had been plotted was to sketch in lightly the 10,000-foot isobars. Here immediately considerable difficulty is encountered, since the pressure data are not sufficient uniquely to define a set of isobars. The C.A.V. development would require that the winds should be strictly gradient and therefore that they, since there is usually a considerable number, should fix the isobar pattern. But it is obvious on a number of maps that many winds are not strictly gradient or geostrophic, especially if one checks the velocities required by the isobars; winds cross the isobars toward low pressure and also toward high pressure, and in the summer in restricted areas in certain extreme cases winds even blow in a direction counter to that indicated by what seem to be reliable isobars. In locating troughs and ridges, which we defined as running through maxima of curvature (see sec. 3, chap. III), this raises the possibility of having maxima of curvature of the winds or streamlines not coinciding with those of the isobars or of having maxima of curvature in one and not in the other. The general sort of compromise which we came to was to draw the isobars as closely as possible both for the pressures and for the winds, particularly wind directions. This can be done to a very large extent, but where there were definite differences the isobars were drawn as pressure lines for the station values. For small troughs, since there were almost never enough pressure values to define the isobar structure closely, we had to be content with putting the trough in the isobars at the maximum wind-shift line while bearing in mind the possibility that this might not be correct. The finding of troughs and ridges and the identification of these components with features on previous maps are extremely important and should not be neglected even if it is necessary to check the 6-hourly winds-aloft maps to be certain of the continuity.

Following sketching of the isobars, the mean temperature at points on the grid was computed from pressures read from the surface and 10,000-foot isobars. The surface pressures were kept on a sheet from which the pressure changes could be figured and plotted at the same time as the mean temperatures were obtained from the graph. The separate computation of the mean temperature at each point is a rather tedious process, particularly in the forecast where one wishes to obtain the surface pressures at a number of points from the forecast temperatures and 10,000-foot pressures. For this we used in later months an approximation noticed by Gilley T. Stephens of the United States Weather Bureau by which, when the forecast isotherms and 10,000-foot isobars are each drawn for intervals of 4 units, the surface

isobars at intervals of 6 mb can be drawn rapidly through the intersections of the other two sets of lines within an accuracy of 1 or 2 mb.²

The next step in the routine was selection of the winds for which C.A.V. paths were to be computed. Each, when picked, was identified by a number consisting of the day of the month and an index number which was usually arranged to rise from the eastward to the westernmost initial positions. This number allows each wind to be readily identified when plotted on the working bases on which the 10,000-foot forecasts were roughed out. Two types of winds can be selected for computation: those which are moving in a straight line with respect to the earth and those which are moving through maximum curvature points, that is, west winds which have reached their farthest north or south positions and are turning anticyclonically or cyclonically, respectively, at their maximum rates. The first kind constitute the majority which can be calculated on most 10,000-foot maps and can be detected in several ways: the most common are points at places where the isobars or streamlines change from cyclonic to anticyclonic curvature or vice versa; in other cases the isobars may be straight for a considerable distance (i.e., great circle tracks); or, finally, the straight current may be located at a place where the isobars change from cyclonic curvature on the left to anticyclonic on the right, looking downstream. As mentioned in the discussion of theory, the winds are assumed here not to be rotating locally at such a rate as to obscure the path curvature indicated by the isobars. The currents chosen should be fairly strong, since those of about 8 m/sec are about the lowest that ever give any consistent results and should be such that the velocity shear is zero. This last can occur either where the flow is of uniform speed across a considerable distance or where it has a maximum velocity in a narrow zone so that near the center the shear, positive on one side and negative on the other, vanishes at the element selected. It is, of course, quite permissible to restrict our winds to those having no shear at the initial instant, but it must be remembered that this may not necessarily continue to be so at subsequent times.

These considerations of shear and strength of flow apply also to the selection of maximum curvature points. In addition, however, several other precautions are necessary, because, instead of measuring the inflection latitude, the speed, and the initial angle (all straightforward), one measures the latitude of the point, the speed, and the radius of curvature

²Vincent and M. B. Oliver, Forecasting the Weather with the Aid of Upper Air Data (Chicago: Institute of Meteorology, University of Chicago, 1944), p. 25.

of the flow. With respect to the curvature it has been our experience that the trajectory patterns for these points work best if the radius (measured from the map with a pair of dividers) is a general one for the flow some distance on either side of the point and not the relatively short one which might be obtained by working with the isobar in only the most immediate vicinity of the point. With respect to the latitude, since β , the variation of the Coriolis parameter along the meridian, is a cosine function of the latitude whereas in the theory it is assumed constant, it makes considerable difference, especially when the path has a wide latitudinal range, just what latitude is used in the computation. If the latitude at one extreme of the path is used, the error will be considerable by the time the other extreme is reached, whereas if the inflection latitude is used, the error with respect to the true path is distributed between both the north and the south branches of the curve. For this reason it is desirable to use the inflection latitude instead of one of the extreme latitudes in computing curvature points.

The computations are performed on a slide rule devised by Professor J. C. Bellamy of the University of Chicago, which is appended at the rear of this paper, so as to be removable.³ It consists of an overlay and an underlay of paper with three groups of scales. The top group is used to compute T from c , ϕ_1 , and the inflection latitude; the middle group to find y_m and y_1 ; and the lowest group to find D . The general procedure is to set c opposite the latitude on the appropriate scales and then read the desired quantity opposite ϕ_1 . For the maximum curvature points the extra scales in the middle group must be used to find the inflection latitude by a successive approximation process of the following kind. y_m is found from the speed, the extreme latitude, and the radius of curvature. This y_m is then added to or subtracted from the initial latitude, according as the initial curvature is cyclonic or anticyclonic, to obtain a first approximation to the inflection latitude. This latitude is then used in the same way to obtain a new y_m , and the process is repeated until the inflection latitude converges to some value. This value should then be used in the calculation to obtain, first, ϕ_1 on the middle scales and, then, T and D in the usual way. In the case of certain cyclonic points with sharp curvature and strong velocities, the values of y_m may not converge at all but constantly increase (because β decreases northward and the smaller it is, the farther north a particle must go in order to lose enough relative vorticity to become a straight

³Mr. Bellamy has also devised a more complicated set of graphs which may be used for computing winds under more general initial conditions.

current). This means that the wind will never reach an inflection point but will always have cyclonic rotation and will produce, other things being equal, a pattern of loops which progress westward.

In measuring the velocities of currents at the 10,000-foot level, we have found, in all but a few of the cases, where the data were sufficient to be perfectly reliable, that the pilot-balloon winds were on the order of 5 to 15 per cent less than the velocities called for by the geostrophic equation. This correction was usually applied to winds measured from the isobars alone when there were no pilot-balloon winds, on the assumption that the pilot balloons are fairly accurate.⁴ A careful study could doubtless derive some forecasting indications from the cases where the pilot-balloon velocities equaled or exceeded the gradient winds or those cases in general where the streamlines deviate from the isobars.

When the path constants had been computed with the slide rule, the curves were sketched on a base map, and the positions of each wind at 24-hour intervals interpolated between values at the quarter periods.⁵

Each wind was then marked on a data sheet with its identification number and the positions up to 6 days identified by longitude and latitude, together with the direction at each position and the original speed, the latter being assumed to remain constant.⁶ A small symbol is placed beside

⁴The reason for this difference might possibly lie in errors of single theodolite runs, but, since it is so general and at the comparatively low level of 10,000 feet, it would seem to indicate, if this is the cause, some revisions in the ascension rate values. On the other hand, if the pilot-balloon winds are accurate, a theoretical investigation of the reason for the discrepancy would seem to be in order.

⁵Though, because we were then unaware of the exact nature of the differences, we did not do so during the year's series, there is a possibility at this point in the procedure of adjusting to some extent for the difference between the spherical case and that in the plane coordinates. Strictly speaking, the paths should be plotted on a square grid with the north and south branches of the curve mirror images of each other, if the consequences of the mathematics were to be followed rigidly. However, we plotted the paths on the 10,000-foot base map, which was a polar stereographic projection, and thus already, through the convergence of the meridians on the chart, made the north branch of the curve smaller than the south branch, as it should be on the earth. But we used the same quarter period for the north as for the south branch, thereby making the northern 24-hour legs shorter in actual distance on the earth than the southern, whereas they should be the same from the assumption of constant speed. Consequently, it would be more consistent in the interpolation of 24-hour positions to take in an extra distance for the northern legs and diminish the southern to make them more or less equal.

⁶See extracts from these sheets on the figures in sec. 1 of chap. III.

each wind to indicate whether it is in a cyclonic, anticyclonic, or inflection portion of the trajectory. The data sheet is then used to plot the work sheets on which the 10,000-foot prognostic charts are worked out, a small copy of the forecast chart then being made so that the 48-hour work sheet today can be erased and used tomorrow for the 24-hour chart. This avoids the necessity of replotting the trajectory winds on a new sheet. The use of the data sheet also makes it easy to keep a running check on the verification of the forecast winds, since every day the observed winds at the computed positions for that day are entered on the sheet (in a color different from the forecast winds), together with the curvature character of the isobars at those positions. (This curvature need not agree with the curvature of the trajectory, since $\frac{2\gamma}{\gamma_t}$ can occasionally be large enough to give c/R_T the opposite sense to c/R_S .)

This, in brief outline, covers most of the daily routine work up to the preparation of the prognostic charts. The only other preliminary to undertaking the forecast is to bring up to date the positions of significant troughs and ridges on the work sheets. These are entered in identifying colors to 3 or 4 days back from each sheet so that the 24-hour work sheet has four previous positions of each trough; the 48-hour, three; and the 72-hour, two. Further, both on the work sheets and on the observed 10,000-foot maps, the monthly mean isobars, after Namias and Smith, were reproduced for reference while making the forecasts. Usually the upper-air charts were prepared first and then used in making the surface forecasts, but this might be altered under certain synoptic conditions, or depending upon the types of use of the charts. An evaluation of the forecast results will be made in the last chapter after we have, in the next, examined a number of the actual forecasting considerations.

CHAPTER III

EMPIRICAL RESULTS

In the present chapter a number of ideas and considerations will be given which seemed useful in forecasting over the areas from which we have had data. Because of the extreme complexity of actual maps and the inadequacy of present theory, it is necessary to do this largely in an inductive mode, that is, essentially by citing of restricted particulars and a marshaling of examples. Though there is a leading theoretical idea, i.e. trajectories, the application cannot be wholly mechanical, and the various ideas based on it and other principles must be balanced against each other in the light of experience and a multitude of empirical details. In fact, specific forecast principles are almost impossible to state adequately without imposing an exceedingly large number of necessary conditions. What has been attempted here is to give a number of specific leads which, with experience as the principal guide, we feel to be capable of being synthesized into a whole which will be of value for the forecast problem.

1. Observed Trajectories

The first point which we will consider in detail through a number of figures is the question of the differences which exist between the trajectories as computed and the true path of the air. An idea of these differences, particularly where the deviation is fairly general, would be of great assistance in using the trajectories as a forecast tool. Figures 9-19 give a number of comparisons of true with computed paths. What is taken to be the true path was determined by measuring the wind direction and speed on the 10,000-foot chart at the initial point from the 6-hourly winds-aloft charts and advancing the particle with this velocity for 6 hours to a new position, the process then being repeated on the next winds-aloft map. The wind changes were generally not great over 6 hours in the currents we checked, so that, while the process is certainly not perfectly accurate, it should give at least a qualitative idea of the differences from the C.A.V. paths.¹ Probably the most formidable obstacle to gaining a correct understanding of

¹This procedure and a more exact one are described in Sverre Petterssen, Weather Analysis and Forecasting (New York: McGraw-Hill Book Co., 1940).

what is occurring is the uncertainty as to the effect of vertical motions through the 10,000-foot level. This is a difficulty also in the theory of the C.A.V. trajectory as applied to one level, since one should follow the original fluid element no matter how it happens to shift in the vertical. However, our experience tends to indicate that, at least in the broad currents, there is enough vertical homogeneity to give useful results even though the particle at the 10,000-foot level may not actually be the same one that we originally began to track. With sufficient pains some of the deviations probably could be traced to this,² but, in operating at one level with the trajectories, we can proceed as though the current were really moving horizontally and apply any empirical corrections which may be determined from that standpoint.

In attributing the deviations to various causes, we have felt that, for reasons which are rather vague and not now backed by unambiguous observational support, convergence and divergence ought to be important contributing factors and have therefore expressed many of the deviations in terms of them, except where other causes are quite obvious. Whether this is justified can be determined only by direct measurement and computation of all the terms in equation (22), which we were unable to undertake on the scale requisite to obtain determinate results. Consequently, caution should be used in drawing secondary conclusions from the descriptions of convergence and divergence in various types of currents. The utility of the predominant types of deviation in estimating future currents is to a considerable extent unaffected by this uncertainty as to their exact causes.

Figure 9 gives computed and actual paths for a current which exemplifies the common pattern of deviation which is mentioned in the discussion of divergence at the end of chapter I. It is a northwest inflection wind starting out behind the moderate upper trough A which was connected with a surface occluded front. Trough A deepened and slowed down over the Middle West and East and finally disappeared in an extensive southwest flow ahead of trough B, which drops in behind it while the whole system approaches the cold-low type. At 10,000 feet between the 2d and the 3d the path swings anticyclonically for a day, while acceleration of the speed begins to occur during the deepening. This would indicate divergence, and, since the shear cannot in this case account entirely for the observed deviation, there is

²A very desirable line of investigation, if a semi-quantitative estimate of the vertical motions could be obtained, would be to see how much of the change in horizontal circulations at fixed levels is due solely to transport of momentum from other levels.

Feb 28 4 105:52 20, -65 94.39 77:45 69:58 47:55 ?
 Sep 24 5 104:48 15, -55 91.40 75:44 64:52 47:55 ?

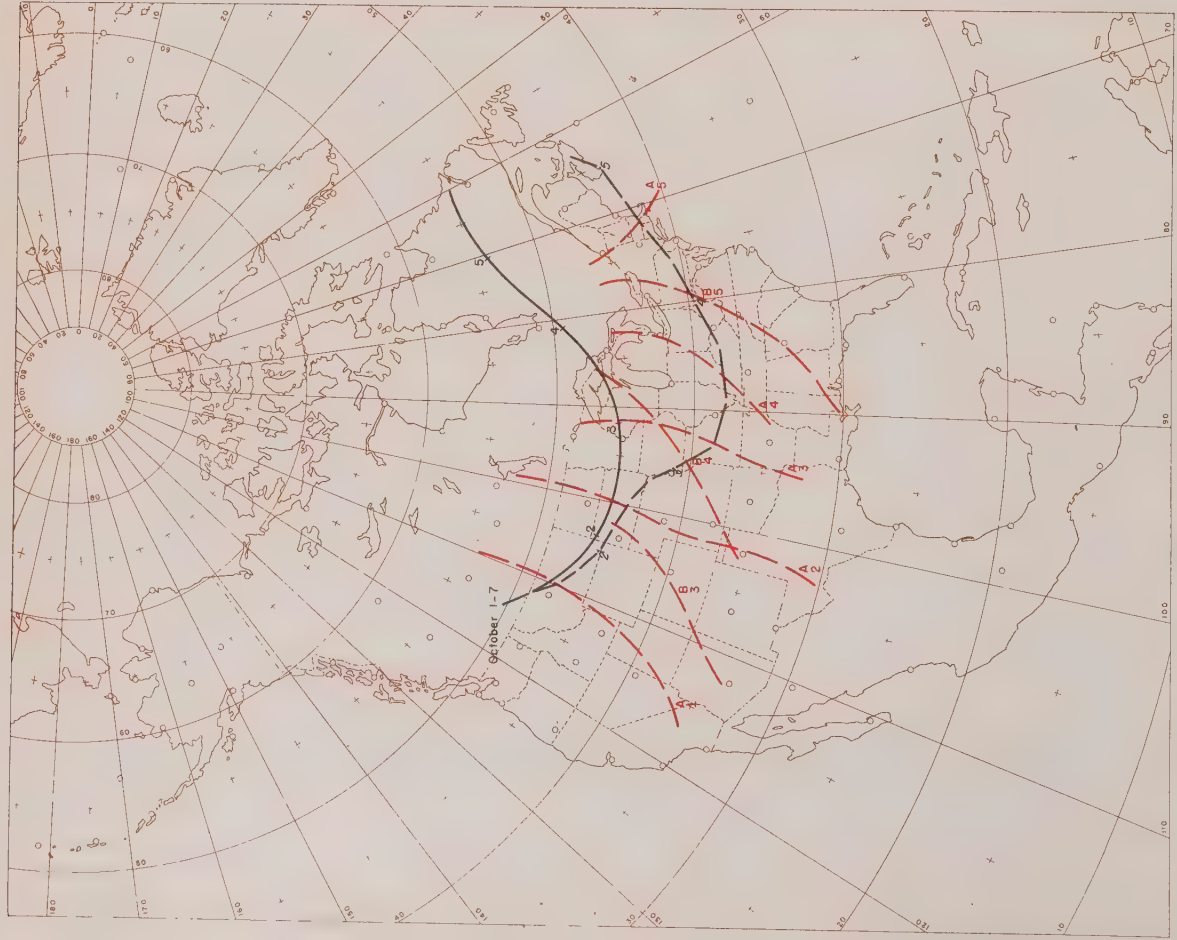


FIG. 9.—Comparison of C.A.V. and true paths for the wind October 1-7. (Numerals along the paths are the dates for positions at 24-hour intervals. The true path is dashed, each dash being the 6-hour displacement extrapolated from the 10,000-foot map for the beginning of the 6-hour period.)

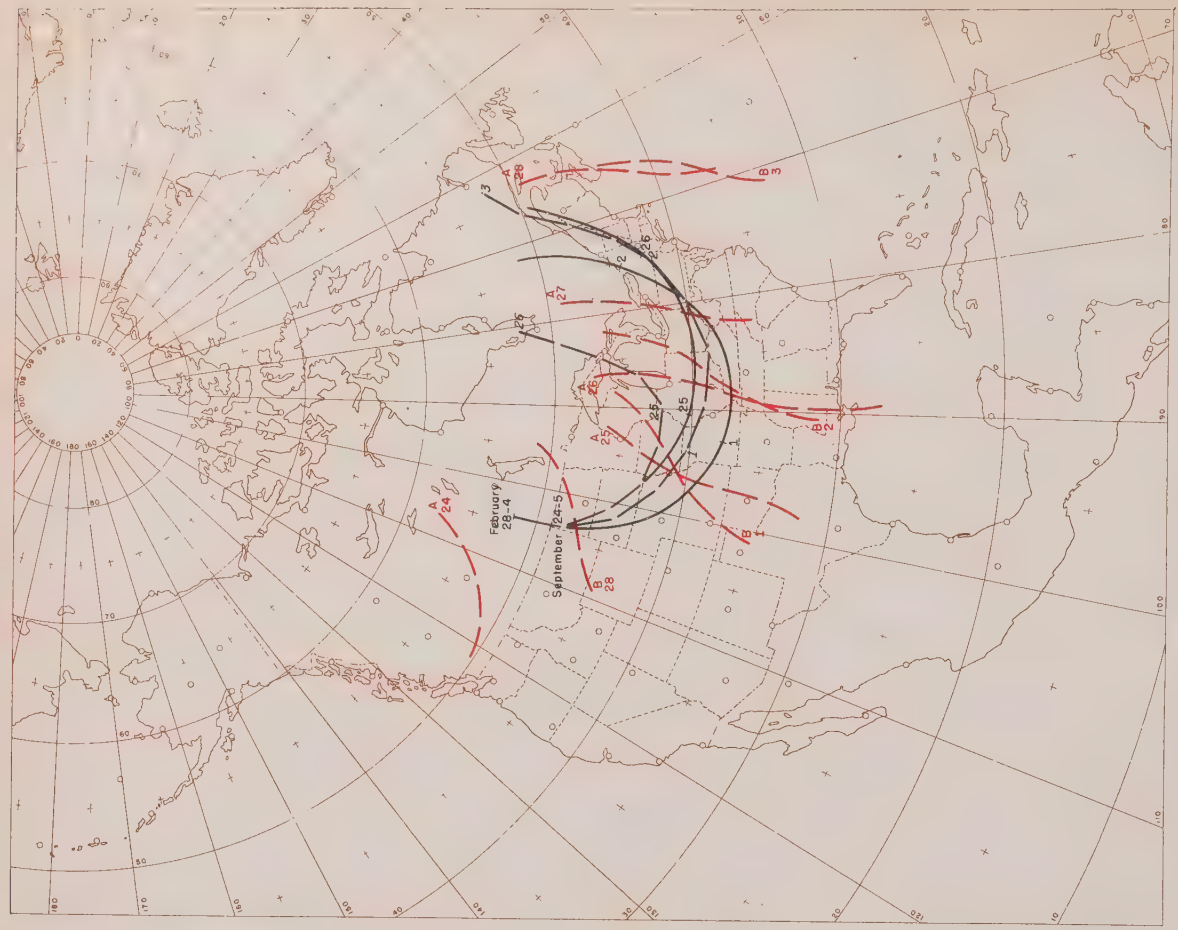


FIG. 10.—Comparison of C.A.V. and true paths for the winds Feb. 28-4 and Sept. 24-5. (See Fig. 9.)

all the more reason to think that divergence is, in fact, present. While there are faint indications on the 10,000-foot maps of some cyclonic shear developing, which would change the path in the anticyclonic direction, this is not great enough to account for the rather sharp turning shown. The evidence of convergence in the southwesterly part of the path is not so clear but is suggested by the tendency around the 5th for the path to keep heading north instead of beginning to turn back. In this case the wind has gone through the trough so that the southwest wind ahead of the trough on the 5th is the same air as the northwest wind that started behind the same trough on the 1st; this corresponds to the cases of cold troughs. This behavior of the wind with respect to the trough means that the normal deviations will operate to shift the trough ahead of positions indicated by the computed winds. When the northwest wind first comes around to west-southwest on the C.A.V. path, the trough should remain behind it, since the wind is going through the trough; but, when the normal deviation occurs, the wind will actually be, say, west-northwest and the trough be located at a position to the east of that indicated by the computed wind. Some ways of estimating roughly the magnitude of this easterly correction for troughs and ridges will be given in section 6.

The succeeding figures of this group, besides having the C.A.V. and actual paths and positions of troughs and ridges associated with the winds (each trough line is labeled with its date and, where necessary, with an identifying letter), also have the check-sheet data on each wind so as to give an idea of how the different types of deviating paths affect the verification at points on the computed path.³

Figure 10 gives two less common alternatives to the type of actual path in Figure 9: Feb. 28-4, where the trajectory corresponds very closely with the C.A.V. path, and Sept. 24-5, where convergence seems to be taking place in the northwest winds. The trough connected with Feb. 28-4 was a nonfrontal trough associated merely with vigorous falls in the mean temperature behind and in the trough. It dropped from the northwest down into a mean trough in which both the isotherms and the isobars had a broad general U-shape before its arrival but were left rather flat (running east-west) when it had crossed the coast line. Note particularly how the wind first moves

³A statistical analysis of the July, 1942, wind verifications is given by H. G. Dorsey, Jr., and G. W. Brier, An Investigation of a Trajectory Method of Forecasting Flow Patterns at the Ten Thousand Foot Level ("U.S. Weather Bureau Research Papers," No. 8 [Washington, D.C., January, 1944]).

Feb 23-10 120-51 6-132 124-47 119-40 114-43 107-117 49 102-52 96-37
 Feb 26-6 113-39 14, 115 115-50 105-40 106-28 96-28 96-37
 Dec 16-6 105-49 17, -62 90-35 74-34 63-55 66-42 58-94
 Apr 1-3 90-53 15, -80 80-42 66-42 58-94

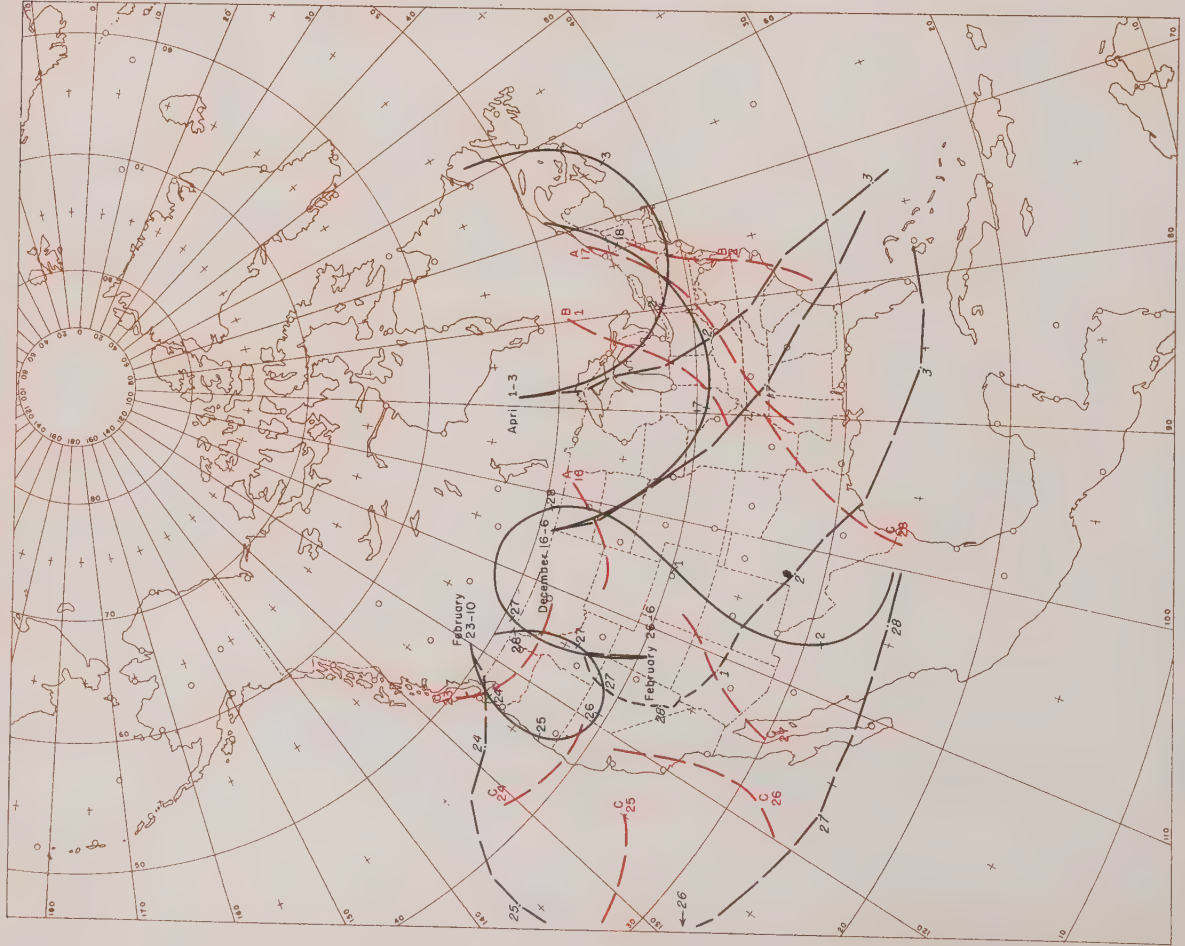


FIG. 11.—Comparison of C.A.V. and true paths for the winds Dec. 16-6, April 1-3, Feb. 26-6, and Feb. 23-10. (See Fig. 9.)

Mar. 8-7 123-49 13, -95 120-35 108-136 102-47 87-60 82-52 77-60
 Mar. 6-4 110-54 15, -70 99-44 83-43 72-56 67-60

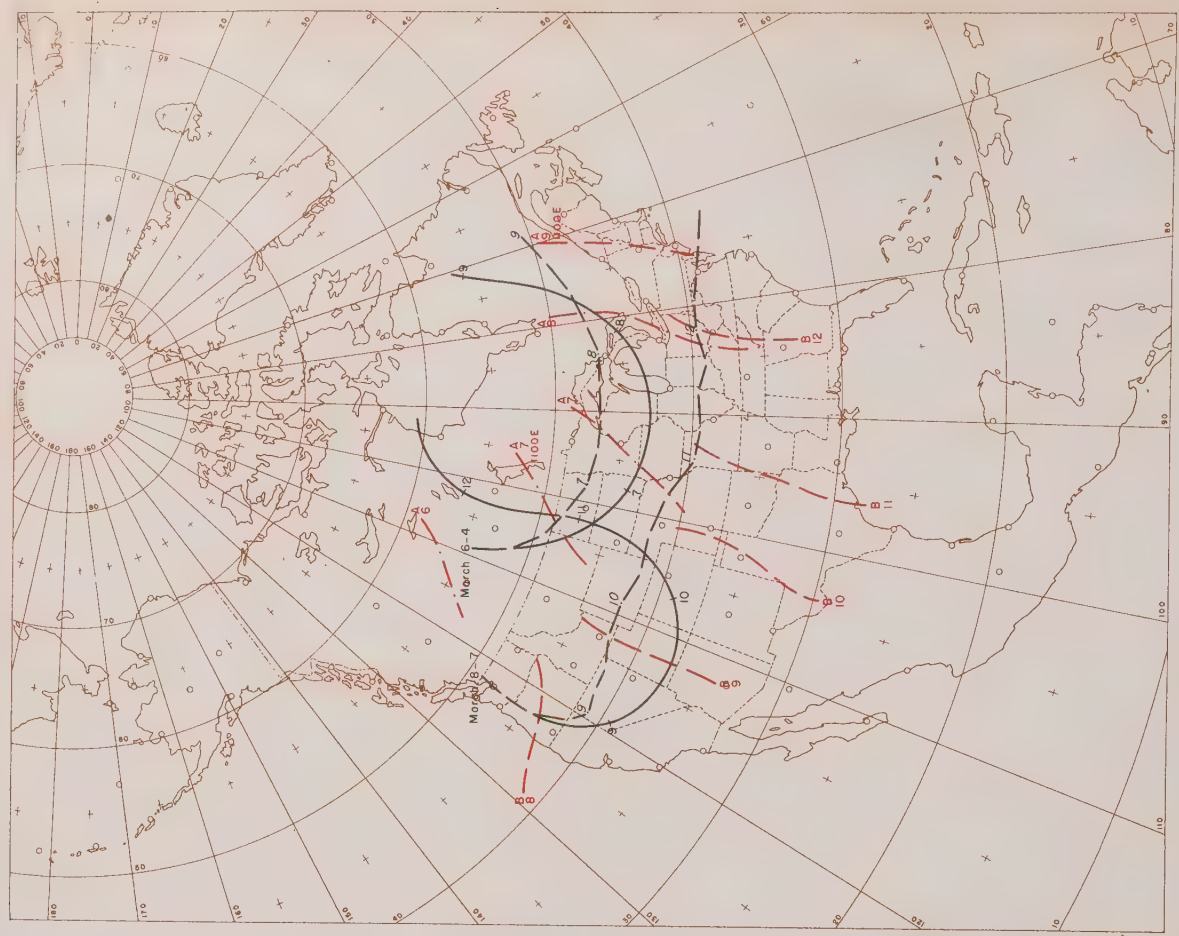


FIG. 12.—Comparison of C.A.V. and true paths for the winds Mar. 8-7 and Mar. 6-4. (See Fig. 9.)

past the trough, seeming to block it, then the trough spurts ahead and catches up to the wind. This inconstancy of the relation of the wind to the trough is sometimes a serious difficulty, and several of the remarks in section 5 are directed toward indicating to some extent the changes of this relation under various conditions. The trough connected with Sept. 24-5 was a Pacific trough which came rapidly over a mean ridge in the west, then deepened very strongly and stalled in the Middle West. The convergence effect on the northwest wind ahead of it is very well marked, and, if anything, the shear is cyclonic on the 25th, which tends to support the occurrence of convergence even more.

Dec. 16-6 and April 1-3 in Figure 11 give a slightly different version of the northwest wind divergence which we encountered in Figure 9. In these two cases, cold outbreaks, which in the April case occurred with a strong deepening trough, have given a straight northwest trajectory all the way out from the United States. What these currents did beyond the borders of the United States was uncertain from our data, but April 1-3 at least probably came back north just east of Newfoundland, since the trough with it seemed to become stagnant at about 55° W. Notice that the trough lines just about travel along with the winds as was the case in the 90° out-of-phase trough which most actual isotherm distributions at 10,000 feet resemble, the warm tongue in the isotherms being some distance ahead of the pressure trough.

In Figure 12, Mar. 8-7 represents a common type of deviation for north winds in which the wind, instead of coming around and back toward the north, moves out on a flat westerly track. On the other hand, Mar. 6-4 gives a fair approximation to the C.A.V. path and, moreover, is a clear-cut case of a streamline feature—the ridge—moving past the wind. The trough with the southwest wind, Mar. 11-5, in Figure 13 is another which moves past the wind, and in this case we have a situation which occurs rather frequently with southwest inflection winds in the New Mexico area. These winds often verify the computations very well while the trough passes them (see Fig. 38 and discussion there). The second wind in this figure, Mar. 11-8a, also is not very deviatory for 2 days, but by the third day it is showing in a mild degree a deviation which occurs quite often when large pressure rises occur in a ridge, the winds then showing northerly components in much more marked degree than those computed (see references to SW pressure rises in later sections of this chapter).

The Rocky Mountain and other ranges in western North America exert a tremendous influence on the air flow over and around the continent, both directly, and indirectly by favoring certain types of air-mass distributions.

Mar. 11-8a 120.55 15.50 10 104.50 75.41 63.50
 Mar. 11-5 102.34 14.30 90.38 78.35 65.31

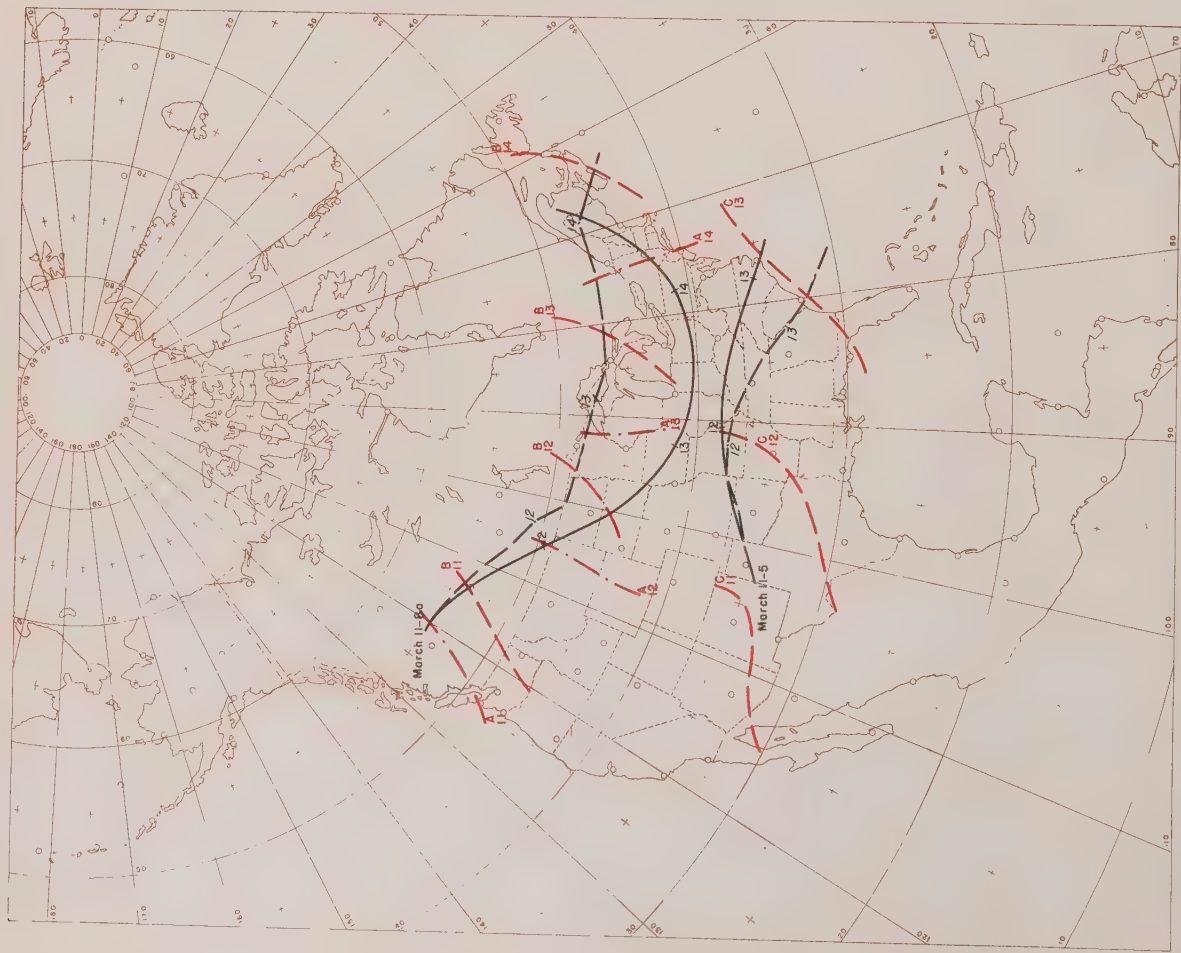


FIG. 13.—Comparison of C.A.V. and true paths for the winds Mar. 11-5 and Mar. 11-8a. (See Fig. 9.)

Apr. 1-7e 165.63 20.30 151.46 111.76 99.45
 Apr. 6-7 128.53 17.45 112.61 91.56 79.49

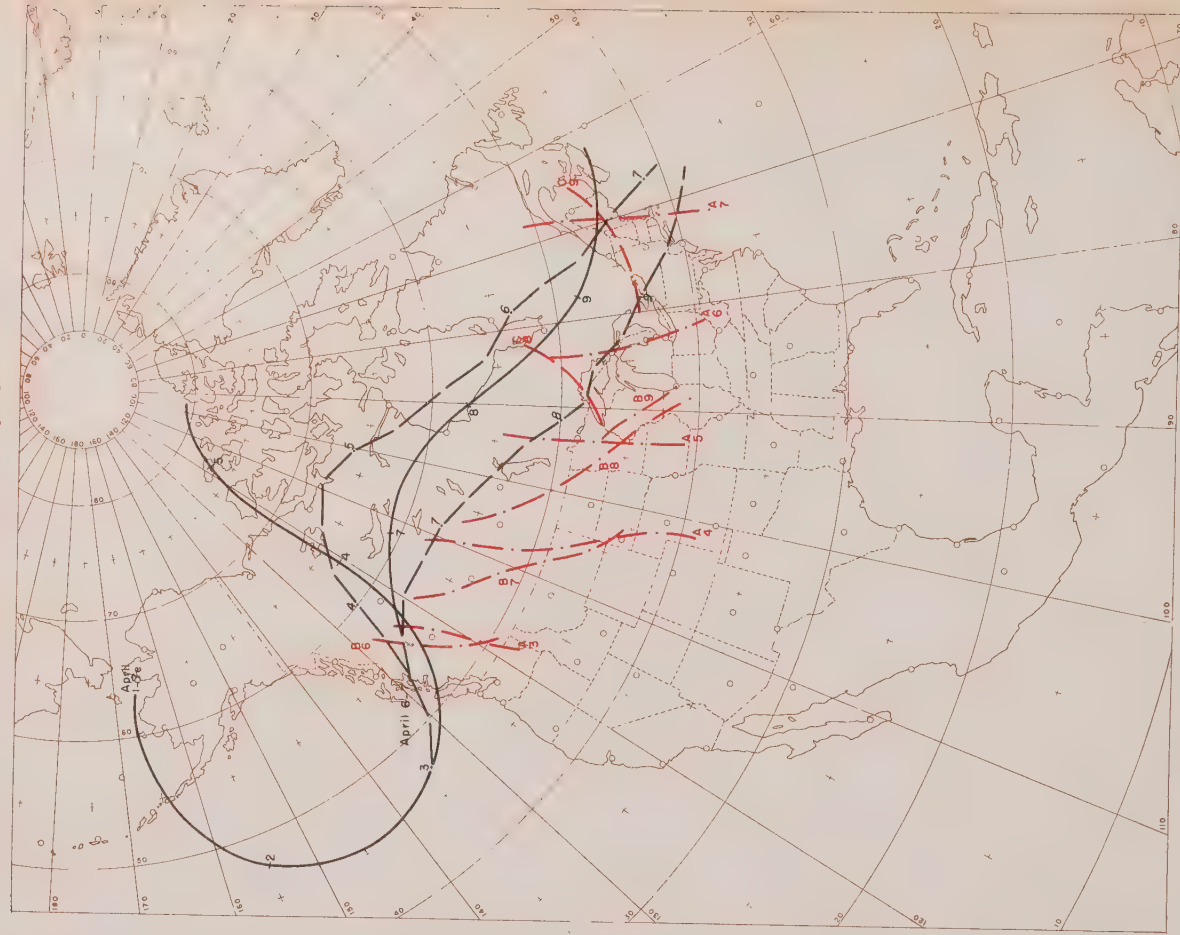


FIG. 14.—Comparison of C.A.V. and true paths for the winds April 1-7e and April 6-7. (See Fig. 9.)

Effects of the mountains are undoubtedly present in all trajectories near them, two of which are shown in Figure 14. April 1-7^e starts in the Bering Sea, but, since our data were somewhat inadequate in the Gulf of Alaska, the measured path was not started until the second day. The verification from the 3d to the 4th, however, suggests that this is not serious. Features on the 10,000-foot charts after the 4th moved in the following fashion: the sharp ridge A ahead of the wind on the 4th moved east to east-southeast while decreasing in intensity and was followed by a number of small troughs which dropped down toward where there was a nearly stagnant surface low and corresponding upper circulation near Newfoundland. The measured path suggests at least two effects operating: (1) the effect of the air masses over the continent and (2) a direct effect of the mountains. The first seems to be at least partly caused by blocking and dragging actions of pre-existing cold flow over the northern prairies, while the second, though undoubtedly complex, is in part probably due to shrinking of the air columns at some stage of the passage across the ranges, leading to an excess anticyclonic curvature of the path. This premature anticyclonic turning is also evident slightly in the case of April 6-7, but here it has the effect only of shifting the path slightly south of the C.A.V. path without greatly affecting the resemblance to the computation. The sequence of events during this time from the 6th onward is different from that after the 4th in that the ridge which replaced ridge A, instead of diminishing in intensity, maintained its strength well across the country; this was associated with the entrance of an active closed low over the western part of the country behind the ridge.

Figure 15 gives two more examples of the mountain effect and one of simple divergence which occurred, however, in an unusual situation. April 13-5 shows the anticyclonic turning due to the mountains very beautifully and later on convergence, to give a more close-coupled path than the C.A.V. The moderate ridge A located on the first day just ahead of this wind moved rapidly southeastward toward a strong mean trough circulation in the East, diminishing in strength and flattening out as it went, until finally it was barely discernible as it crossed the Atlantic coast. The trough behind came later with a vigorous surface low along much the same track and was very pronounced when it passed the Lakes, this being associated with the convergence effect on the wind. April 20-3, on the other hand, started out much farther behind its ridge, and the ridge, instead of diminishing, remained much the same and eventually developed a closed warm high over the Lakes. The effect on the wind is to counteract the mountain influence, which only shows for a time and is followed by a return to a fair approximation to the computed path.

Apr. 13-5 127.55 20, 57 110.66 85 60 70.46 48-45
 Apr. 20-3 20.54 21, 43 96.63 71 56 49 47 46-45
 Apr. 22-5 95.40 20, -50 79.32 62 39 46 48

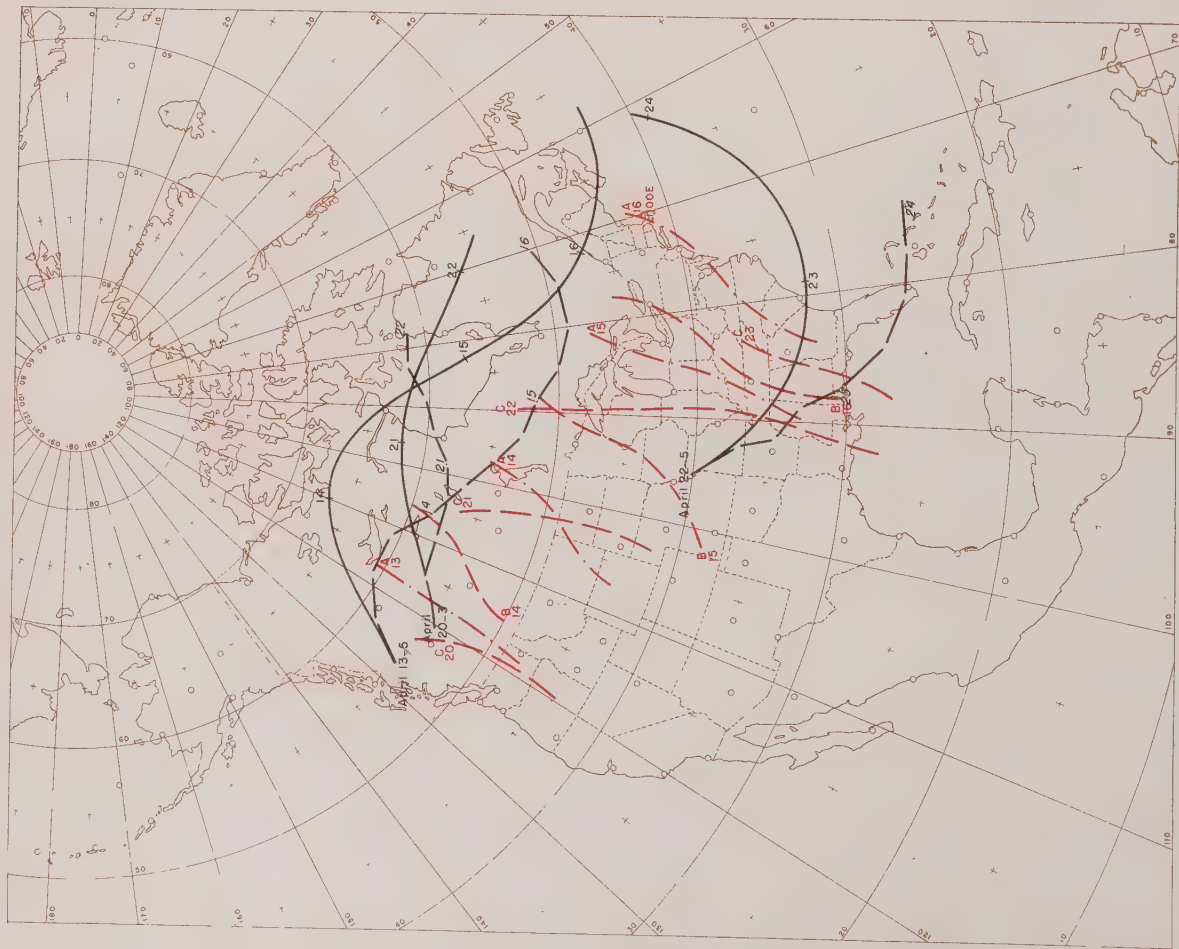


FIG. 15.—Comparison of C.A.V. and true paths for the winds April 13-5, April 20-3, and April 22-5. (See Fig. 9.)

Mar. 28-9e 150.62 14, -50 142.51 112.67 113.57 114.2
 Mar. 31-8 129.53 16, 70 119.62 98 60 90 49 75 42 80 49 89 40 101 47 79 31 62 34
 Mar. 29-4 115.38 18, 60 101.47 89 40 79 31 62 34

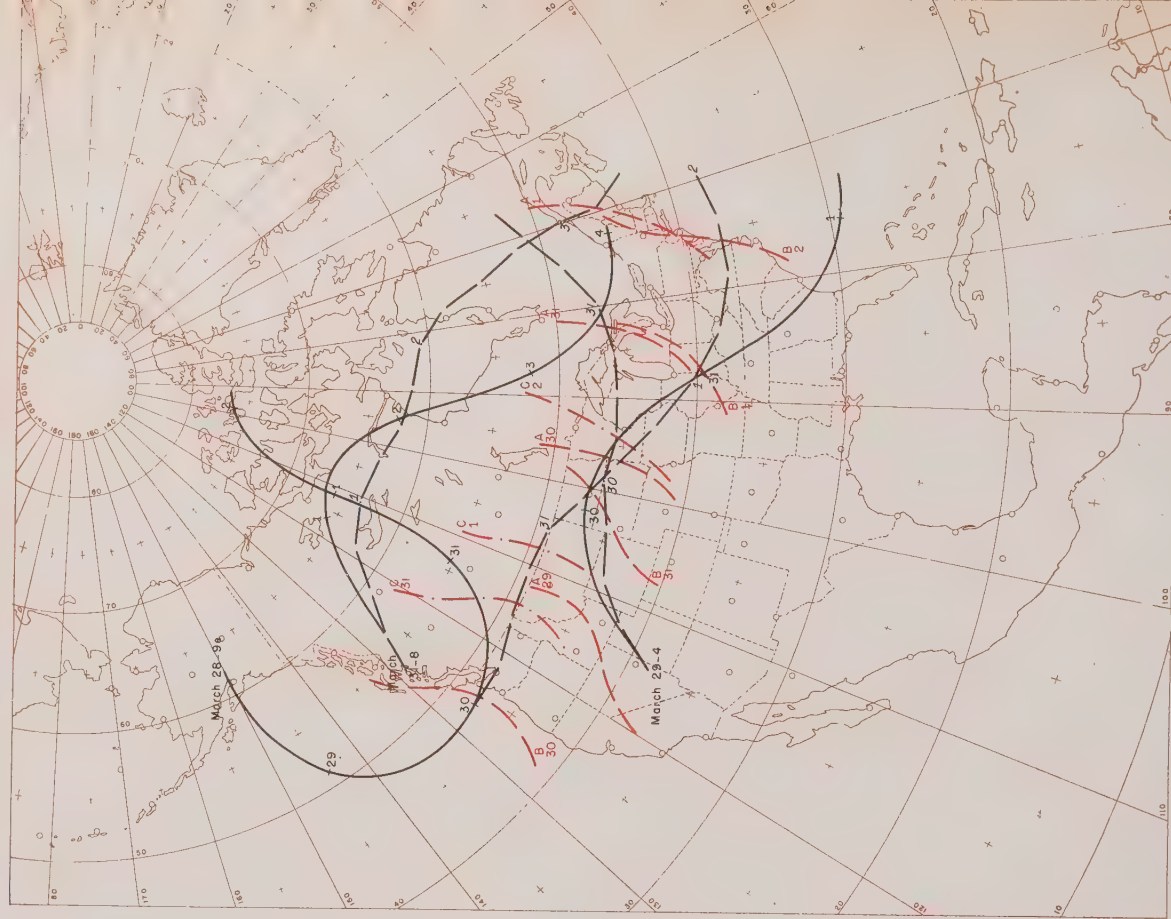


FIG. 16.—Comparison of C.A.V. and true paths for the winds Mar. 28-9e, Mar. 29-4, and Mar. 31-8. (See Fig. 9.)

The last wind in Figure 15—April 22-5—was picked in a strong northwest flow behind a long meridional trough along the Mississippi River. This current was the strongest of those in the eastern United States and seems to have been the determining influence on events there. On the 23d a closed low at 10,000 feet of a low latitude character formed to the left of this current. At the same time the surface low was moved toward the southeast, diminishing from its already weak state and being attended by the weak upper low as it moved beyond range off the Florida peninsula (the 10-km chart went through practically the same sequence of events as the chart for 10,000 feet during this situation). The formation of the upper low and the movement of the whole system seemed in this case to be directly connected with the northwest current; the predominating effects were banking to the right of the current to produce the upper low and steering of the whole system toward the southeast by the strongest stream.

The trajectories in Figure 16 show several interesting miscellaneous features. That for Mar. 28-9e follows a pattern which occurred quite generally during the series. That is, when a strong cold north current sets in toward the Gulf of Alaska, a vigorous westerly circulation with quite pronounced troughs ensues over the United States, giving a path of the kind shown. Compare this with the Bering Sea north wind in Figure 14, which occurs only 4 days later. The considerable difference between the two is, we think, to be explained mainly by the difference of the distances of the currents from the continents and the effects which this has on air-mass distributions and movements.

Mar. 28-9e, when it has crossed the mountains with its associated trough, sets off moderate deepening of the trough connected with Mar. 29-4; this wind in consequence shows the normal southwest convergence effect. In this case of deepening associated with a trough overtaking another (see sec. 3h) there were discernible surface fronts with each of the troughs at 10,000 feet, but there need not necessarily be fronts with both; one, usually the western one, may be plainly evident only on the upper chart. The third wind in this figure—Mar. 31-8—exhibits deviations which have been difficult to relate to any particular cause. The ridge over which it was traveling was one between a strengthening cold northerly circulation in the East and strong southwesterlies which came in from the West Coast; and, while there are not sufficient data in Canada to say for certain, there are indications in the winds in the northern United States that the failure of the wind to turn back was due to velocity convergence between the strong winds behind the ridge and weak winds in the crest. The eventual turning

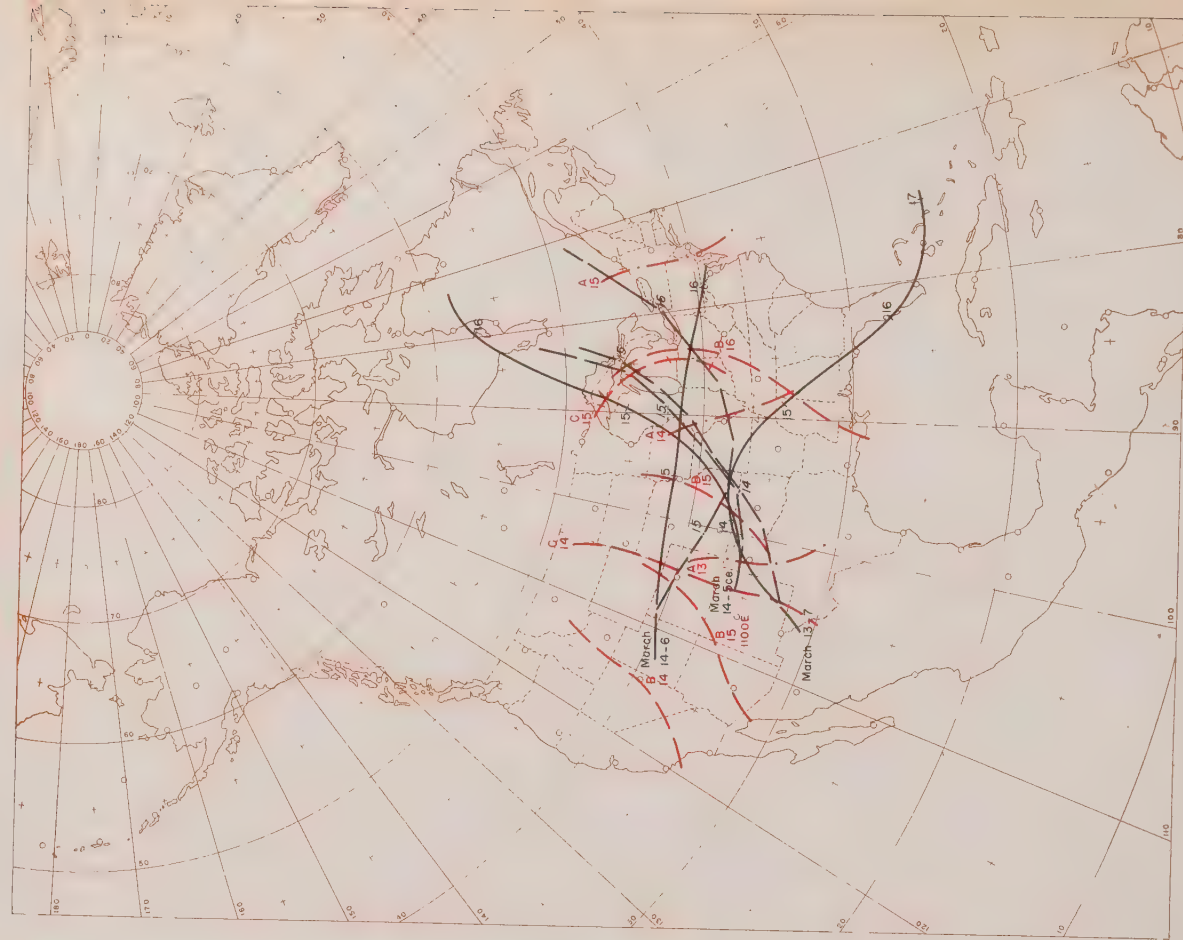


FIG. 18.—Comparison of C.A.V. and true paths for the winds Mar. 13-7, Mar. 14-5^{ce}, and Mar. 14-6. (See Fig. 9.)

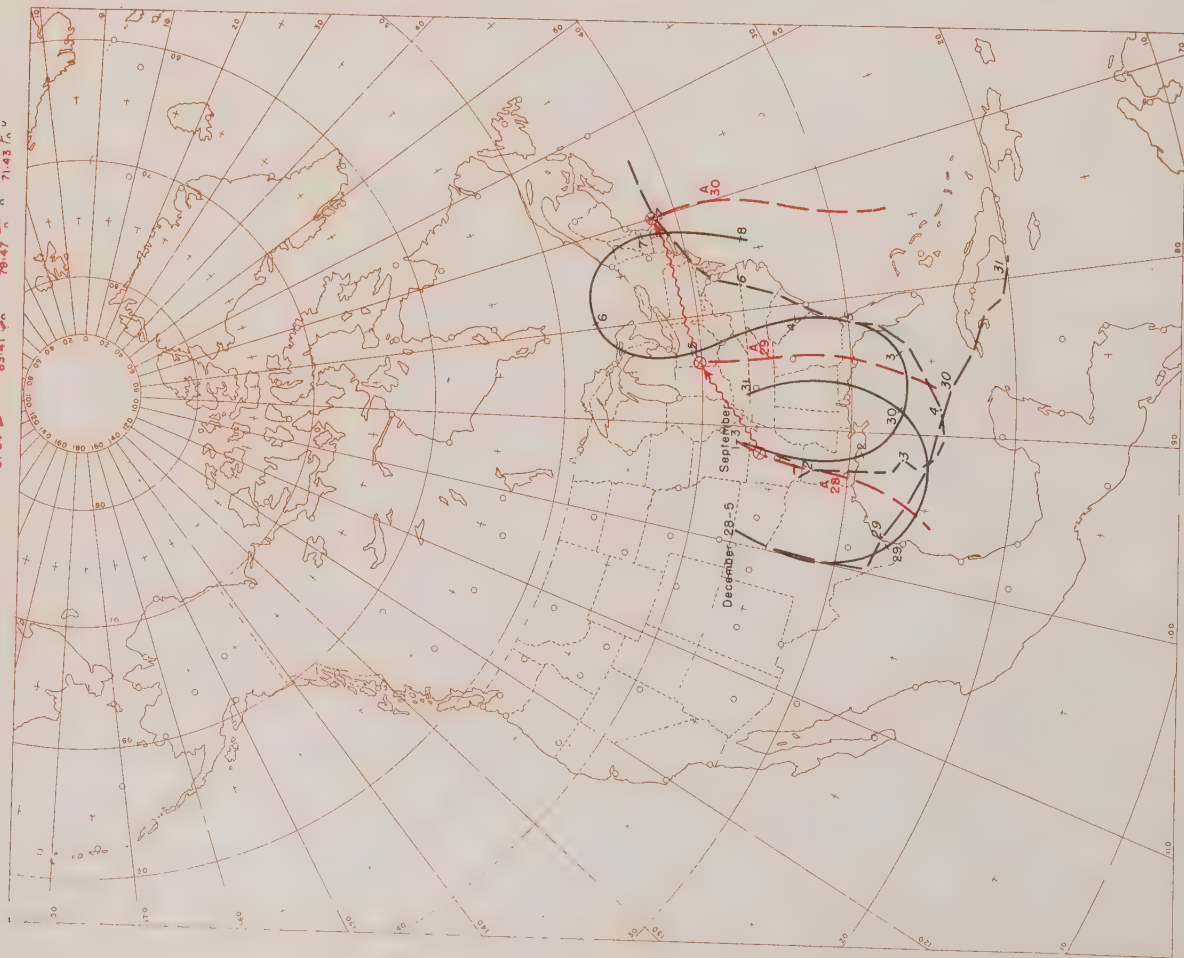


FIG. 17.—Comparison of C.A.V. and true paths for the winds Dec. 28-5 and Sept. 1-3. (See Fig. 9.)

southward occurred through dragging when the current was drawn into the vigorous northerly circulation in the East.

This dragging action is a large-scale process which shows up particularly clearly in the two February paths of Figure 11. That for Feb. 26-6 shows a sharp shift of direction in the first day which almost certainly could not be due solely to stretching of the air column and, in fact, was caused by a very strong west-northwest and northwest flow of partly Pp and partly accelerating Pc air masses over the plains to the northeast of the air parcel we are considering. The mechanism of this dragging is probably partly turbulent mixing and perhaps partly changing of the pressure gradients through banking of the air to the right of the strong current. Dragging was instrumental in keeping Feb. 23-10 far to the south on a flat westerly track in the later part of its path, but the acceleration at the beginning was connected with another major factor which is a frequent ingredient of many weather situations that leads to certain types of low-index conditions. This factor is a large pressure rise seeming to come from the southwest which greatly intensifies a ridge already present in the Gulf of Alaska, followed by acceleration of the currents on the eastern side of the ridge (see sec. 3h, 5a, and 7). Deviations due to the dragging factor have a very marked seasonal change, being strongest or occurring at all only during the cold seasons with strong circulations and Pc outbreaks. For instance, the situation for Feb. 23-10 was almost duplicated, except in intensity, at one time in September, 1942, and in that case the northeast wind at Seattle came around closely as expected from the C.A.V. path, a ridge built up east of and along the Rockies, while the Gulf of Alaska ridge retreated westward, and a weak closed low circulation between the two ridges first retreated westward, then came back on to the coast 2 or 3 days later.

A similar seasonal difference is shown in Figure 17 between Dec. 28-5 and Sept. 1-3. The December track was associated with a deepening low which picked up considerable speed on the 30th with the help of an approaching trough from the west, while in September the upper low was weak, did not have an appreciable supply of cold air, and eventually disappeared as the Bermuda high increased its domination of the East Coast. The checks on both these winds are equally bad after the first day, even though the September track has more resemblance to the C.A.V. path, this being due to the slow-up in the Gulf which leads to a phase shift between the observed and computed September paths.

One of the most difficult forecasting problems is that of determining whether and when an upper low or trough is going to deepen. Assuming that some of the points which we will bring up help to determine this, it is

Mar. 23 8ce 157.41, 20, -38
 Mar. 24 7e 135.49, 21, 47
 Mar. 25 7e 117.45, 14, 48
 Mar. 22 5 115.38, 14, -90
 96.55 120.60 96.55 80.43 58.43 41.56
 73.41 50.47 31.57
 80.41 66.38 53.45
 97.41 91.49 81.42 81.33

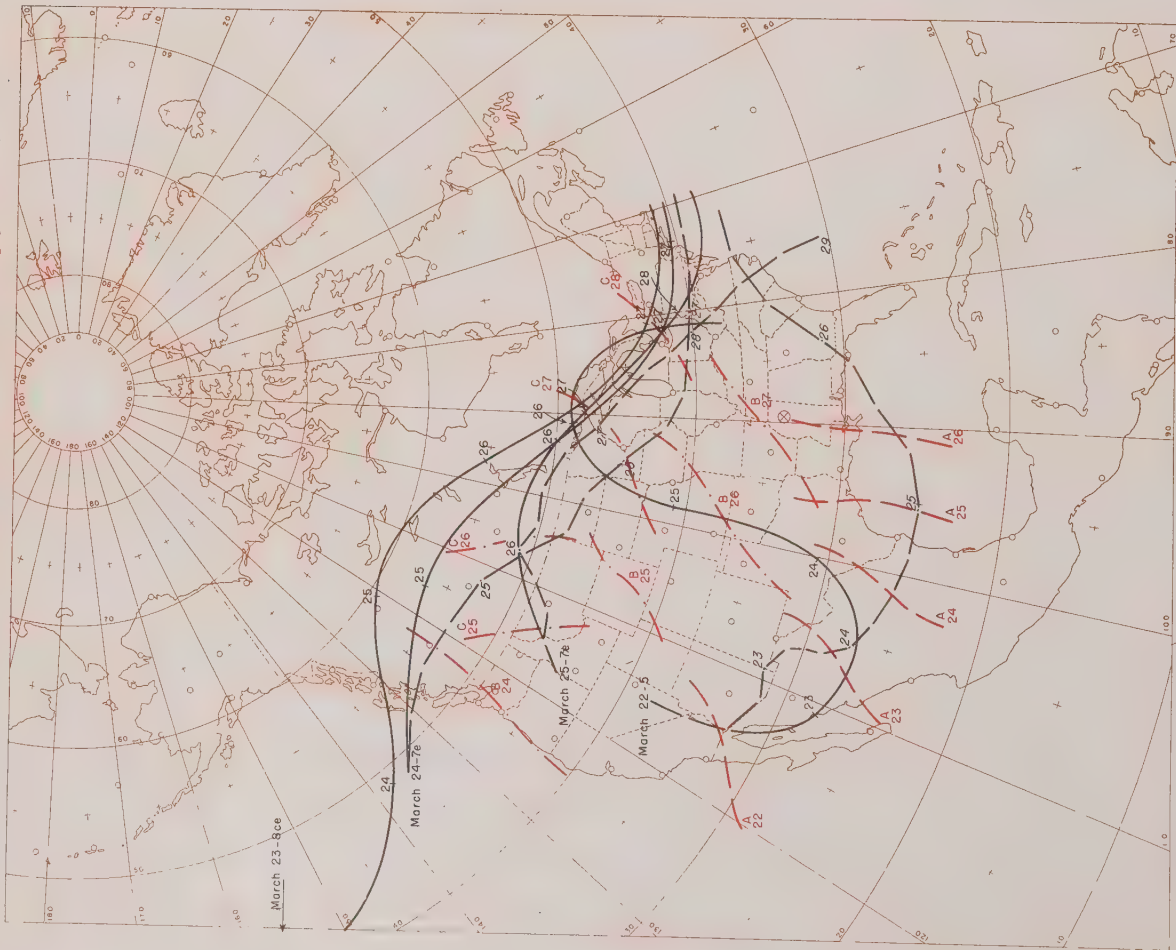


FIG. 19.—Comparison of C.A.V. and true paths for the winds Mar. 23-8ce, Mar. 24-7e, Mar. 25-7e, and Mar. 22-5. (See Fig. 9.)

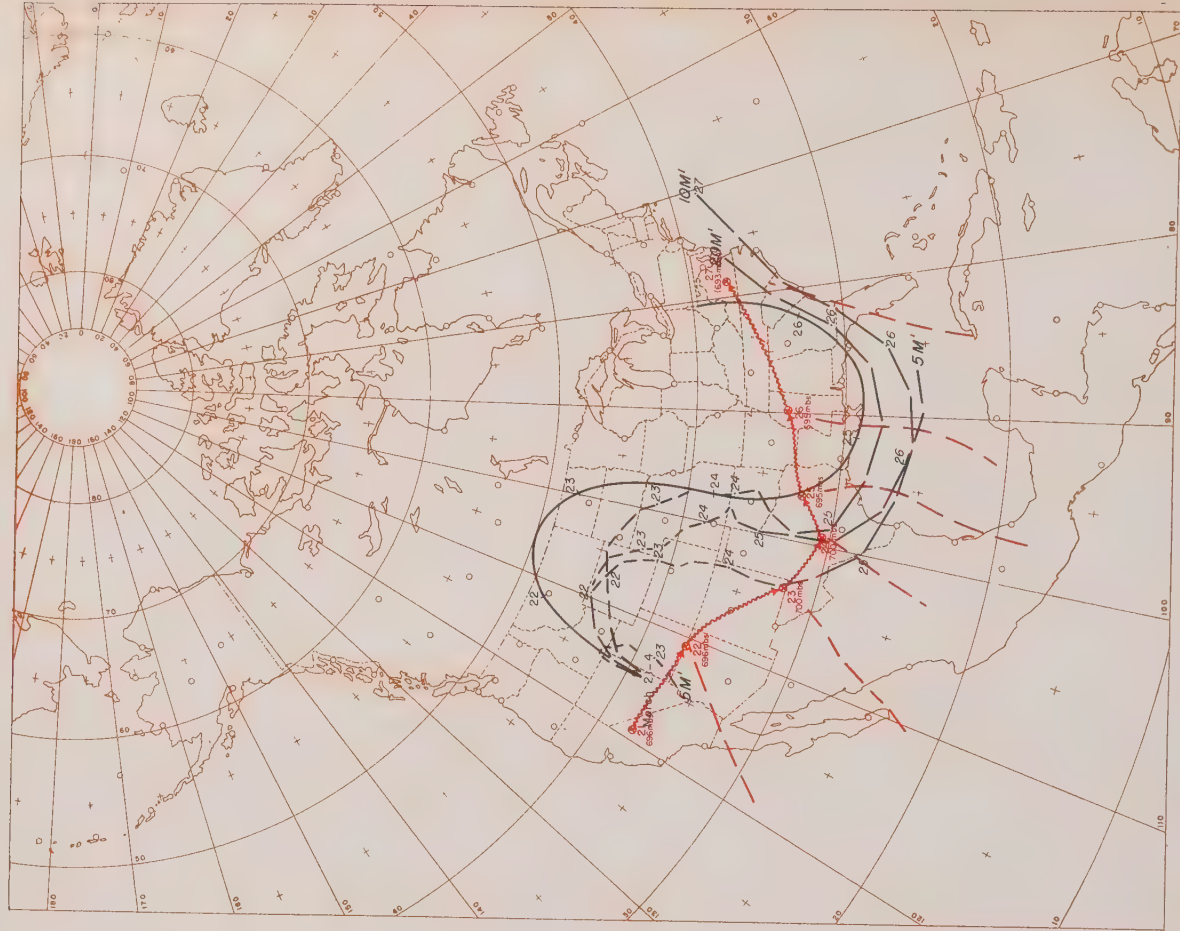


FIG. 20.—C.A.V. path at 10,000 feet and true paths at 5,000 feet, 10,000 feet, and 20,000 feet for the wind Mar. 21-4. (See Fig. 9.) Pressure at the daily positions is the minimum pressure in the 10,000-foot layer.

wise to have some idea of the types and magnitudes of deviation from C.A.V. trajectories that are to be expected when deepening does occur. Figures 18 and 19 give trajectories around two upper low systems which illustrate some significant points. In Figure 18 a straight deepening process was involved. Observe: first, Mar. 14-5ce is an example of how well a good number of cyclonic points work out. But note that the trough C, which originally goes with this wind, is not the one which becomes deep. Trough C goes up in the southwest winds, weakens, and disappears, while trough A behind it becomes the principal feature. Second, the point Mar. 14-6 with this second trough is first evidently turned by the mountains and then, affected by convergence and the accelerations ahead of the trough, turns and moves toward the northeast. This same effect is evident in Mar. 13-7, where the measured path never does turn back toward the south as a C.A.V. path would. Finally, there is a suggestion toward the end of the check sheet for 14-5ce of the type of tracks which some of the winds around closed low centers must follow, that is, looped paths where the relative vorticity is so high that the changes due to latitude are relatively minor and are completely dominated by the initial high vorticity and by convergence effects.

The paths given in Figure 19 occurred around a subtropic upper low in the southwestern United States which deepened up to March 25 and 26, then filled and became a simple trough on the 27th as the strong Pp currents from the west came through to the north of the low; this result was presumably due in part to the cutting-off of the supply of cold air for the low. Starting out behind the low, Mar. 22-5 shows a peculiar jog at the mountains, then shows the general divergence effect, and, finally, between the 26th and 27th, shows a deflection to the right caused by dragging from the strong Pp flow over the Lakes. The other paths are very similar to the computed trajectories except for a few differences of the types already mentioned. This case is quite encouraging because it is one in which the trajectories, by showing the strong current cutting across to the north of probable later positions of the upper low, give a reasonably direct clue to the filling which occurred.

2. Observations of Convergence

Some further data on upper currents around the same low as that involved in Figure 19 are given in the next two figures. Figure 20 gives computed and actual trajectories at 10,000 feet for the point Mar. 21-4 together with 5,000-foot and 20,000-foot measured paths starting from the same position near Fly, Nevada. As can be seen, the 10,000-foot and 20,000-foot paths are quite close to one another, and, though the original air around 5,000 feet is trapped in the Salt Lake Basin, when a new path at

this level was started on the eastern slope of the Rockies, it nearly coincided with the 10,000-foot and 20,000-foot paths until the last couple of days. In view of this fairly close coincidence of the paths at these different levels, an attempt was made to see what changes as regards shrinking and stretching had occurred in the original air column. This was done by taking the two or three radiosonde soundings nearest the trajectory positions at each 12-hour interval and determining the equivalent potential temperature at 2,500-foot levels⁴ up to 22,500 feet by linear interpolation between the sounding curves for the estimated position of the portion of the column at each level. This information was plotted on the cross section of Figure 21 according to approximate distance along the path, together with potential temperatures for levels above 22,500 feet; at the high levels, however, it is doubtful whether the same column is being measured. Since the equivalent potential temperature is conservative for adiabatic processes and for evaporation,⁵ it should identify individual sections of the column in so far as nonadiabatic processes are absent and the radiosonde observations accurate. Not enough reliable data are at hand to make any rigorous statements, but several interesting points do seem to come out.

First, if the equivalent potential temperature is interpreted as a strictly conservative quantity, the Θ_E lines show an excessive amount of vertical motion (they would imply air disappearing into the ground on the 25th); so that it seems almost necessary to conclude that radiation or mixing processes account for some of the Θ_E changes (presuming, of course, that we have succeeded in following the original column). Heating and influx of moisture are quite evidently progressing in the levels below 10,000 feet during the last couple of days; however, this evaluation is affected in part by a lagging of the layer below 5,000 feet which was not allowed for in selecting the later soundings. Even with these reservations it is evident that a considerable amount of vertical motion is affecting the 10,000-foot trajectories. However, the tendency to vertical homogeneity, as shown at least by the resemblance of the 20,000-foot to the 10,000-foot path, will minimize the deviating effect on the paths.

⁴The same or similar procedures have been used by a number of British authors writing in the Quarterly Journal after 1936; i.e., Hewson, Longley, and others.

⁵This is not strictly correct as regards evaporation. See W. Bleeker, "On the Conservatism of the Equivalent Potential and the Wet-Bulb Potential Temperature," Quart. Jour. Royal Met. Soc., Vol. LXV (1939).

Second, the attempt to show shrinking and stretching of the column is made doubtful by the uncertainty as to whether the equivalent potential temperature is a conservative property. The vertical shrinking necessary to cause the premature anticyclonic turning of the 10,000-foot path is vaguely indicated in the approach of the 305° line to the ground level between the 21st and 22d, but this anticyclonic turning also may be partly due to the decrease in velocity which occurs, since from equation (11) a given amount of relative vorticity corresponds to sharper turning with small than with great velocities. The convergence shown in the columns singled out on the figure during the first half of the 23d could have helped to reduce the sharp anticyclonic curvature of the path; the change in latitude is not sufficient here to account for the changes in curvature which occur. Also the divergence in the same column during the early 24th coincides rather nicely with the tendency later to an anticyclonic swerve near midnight of the 24th. The most definite occurrence, however, is the large amount of vertical stretching indicated between midnight of the 24th and midnight of the 25th in all the lower levels. This stretching is coincident with the deepening of the 10,000-foot low by 5 mb and with a large increase in the wind speeds, tending to reduce the cyclonic turning of the path which otherwise probably would have been much sharper than it is. According to the tendency equation (1), since the temperature advection was slight, the convergence, which occurs to at least 30,000 feet, should have led to pressure rises at all the lower levels in the current. Since it did not, but, on the contrary, pressure in the current fell at the surface, 10,000 feet, and probably 30,000 feet, horizontal divergence or replacement of the top of the column by lighter air must have occurred to an intense degree at very high levels. Unfortunately, the soundings of the 25th are not high enough to give any direct evidence.

In order to check on the applicability of the equations relating the depth of columns to the latitude change in a straight current,⁶ the material in Figures 22 and 23 was worked up. A situation at the end of April, 1944, was selected, during which almost due-south flow prevailed in the Mississippi Basin for almost 2 days in a return stream of old polar air on the western side of a moderately strong high. Trajectories were then determined by the method already described (using the 6-hourly winds aloft maps for 2, 4, 6, 8, 10, and 12,000 feet) and are given in Figure 22. Since the selected current proceeds practically straight toward the north

⁶See note, p. 21.

and the horizontal shear was not appreciable, the depth of any section of the column should increase proportionally as the sine of the latitude, or over the full 2 days here approximately as $(\sin 55)/(\sin 34) \approx 1.5$. The cross section along the path in Figure 23 shows the temperature, potential temperature, equivalent potential temperature, and the mixing ratio at each of the above levels and at 20,000 feet, as determined from radiosonde observations taken at 12-hour intervals. The θ_E values do not, however, seem to work out as identifier elements, since a progressive decrease to values below any on the southern soundings takes place, particularly around 6,000 feet (the very low values in the surface layers in the north probably do not belong to air from the original column). This decrease is partly due to radiation and partly to isentropic mixing with dryer air, since an inspection of the isentropic charts for the pertinent dates shows a decrease of over 100 mb in the condensation pressure at the isentropic surface of 302° along the path of the column. In the general area around the column all along the track the clouds consisted of high Ac and Ci almost all above 10,000 feet, and very little if any precipitation occurred, so that from the standpoint of condensation there is little to rule out use of potential temperature as a tracer element. As a matter of fact, the potential temperatures in the intermediate levels show a fairly reasonable pattern, and the four lines which are drawn do show the anticipated spreading. Both for the column indicated explicitly and for that defined by the lower three θ lines the increase in depth over the 2 days is about one-half of the original depth.

While no more than suggestions of what might be occurring can be derived from these two examples because of the many uncertainties involved, it appears plausible, for instance, that the relation between the depth of straight currents and the sine of the latitude might be useful in estimating vertical motions, and therefore clouds and precipitation. This may be done more or less quantitatively both for currents which remain straight and for those which are expected to deviate to one side or the other.

3. Troughs

In most procedures of forecasting from synoptic maps one is interested in types of streamline pictures ultimately as a means of deriving the weather to be associated with an expected streamline pattern which is either explicitly formulated in a prognostic chart or constructed in the forecaster's mind. But a major part of the process of obtaining a set of forecast streamlines or isobars consists of extracting from the preceding set of patterns an idea of the pattern most likely to result from them. We cannot give an extended description of the relation between weather

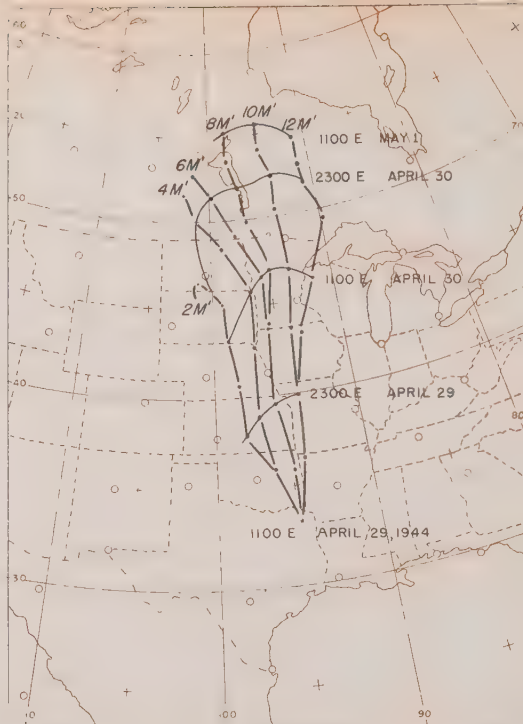


FIG. 22.—True paths at 2,000 feet, 4,000 feet, 6,000 feet, 8,000 feet, 10,000 feet, and 12,000 feet from a point near Oklahoma City on April 29, 1944, 1100 EST.

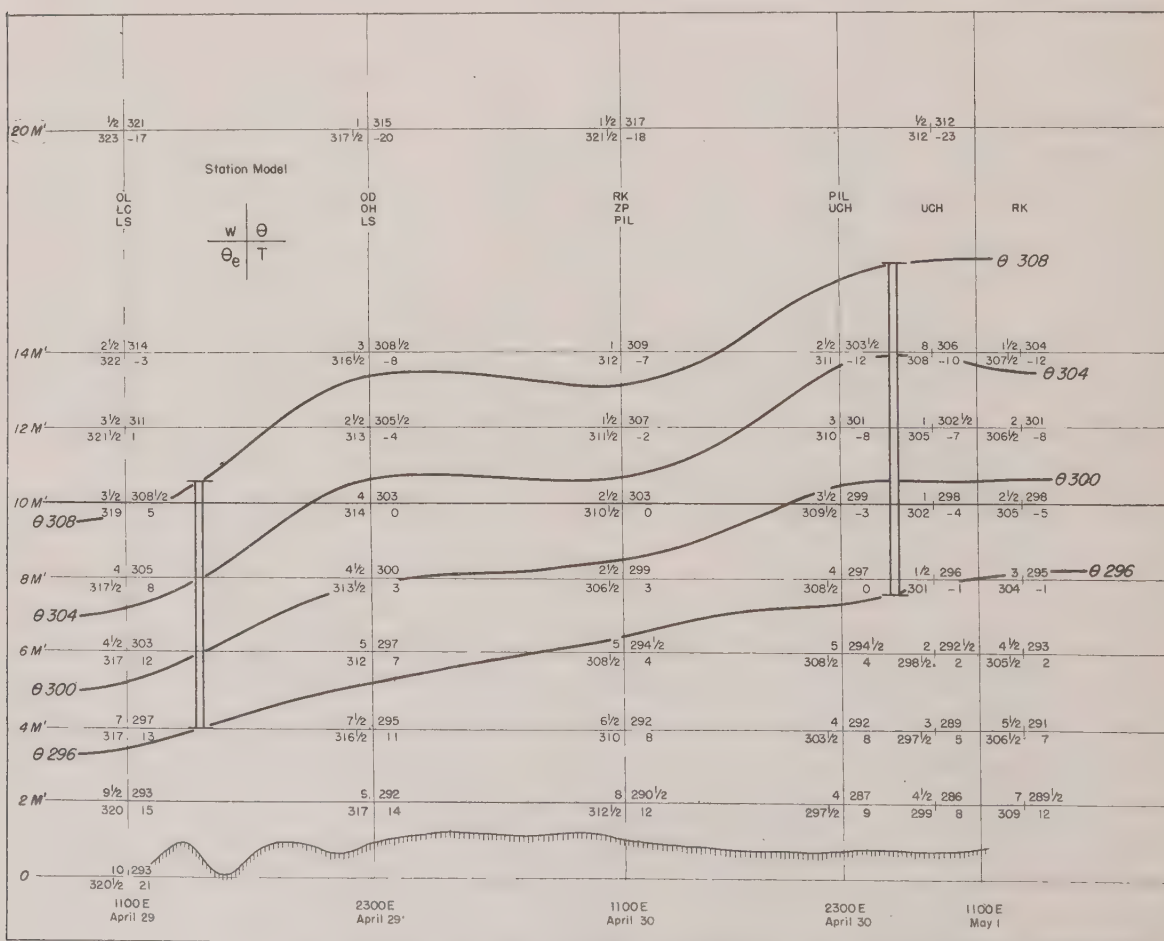


FIG. 23.—Time cross section with lines drawn for potential temperature along the path of the wind from Oklahoma City on April 29, 1944. (Call letters along the top of the figure give the radiosonde stations which were used in interpolating the data.)

and streamline pattern, but the present section and the succeeding one will give a classification of troughs and ridges that was gradually evolved during the year's experience and which has proved of some merit in formulating the forecast of the streamline pattern. In later sections we will consider in more detail the relation of the trajectories and their changes to the streamline features. The categories given here will be seen not to be mutually exclusive or to be formed on a uniform basis of division but are those that have been found most helpful. Further experience will no doubt suggest a more exhaustive and logical system.

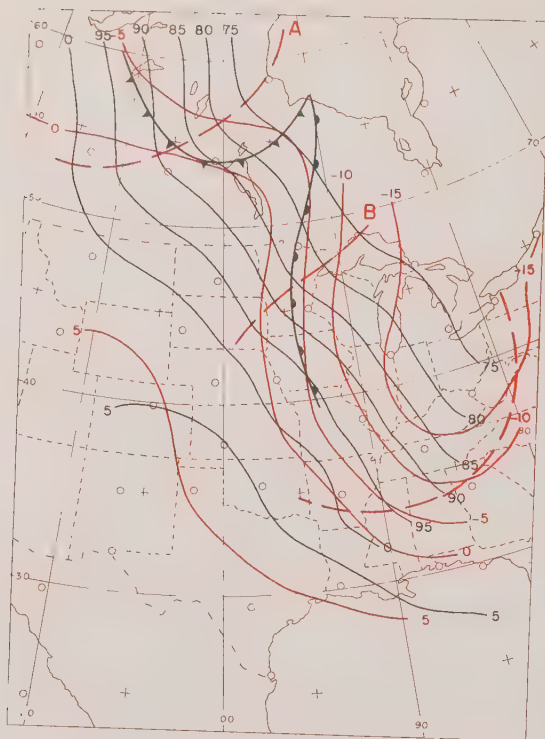
The trough lines on the 10,000-foot maps were drawn in accordance with the following definition: first, that the pressure should be a minimum at the trough line in a direction roughly perpendicular to it and, second, that there should be a maximum of cyclonic curvature of the streamlines or isobars at the trough line.⁷ (The definition for ridge lines is entirely analogous.) This is slightly different from the frequently used convention of drawing the trough line through the points at which the isobars dip farthest south. Actually a majority of important troughs particularly will satisfy both definitions, but there are cases in which it is important to follow a trough that is not located at a maximum southerly position of the isobars. In the case of perfectly circular isobars the maximum curvature condition breaks down, since there is no maximum: in these cases we revert to the other definition.

One further definition of terms is needed at this point: in speaking of the movement of troughs and occasionally of other features, we will refer to movement on the southern, middle, northern, or arctic circuits according as the trough moves mainly in the latitude belts 30° to 40° , 40° to 50° , 50° to 60° , or north of 60° , respectively. There will, of course, be numerous cases in which the trough extends across more than one belt (when it will usually be referred to as "extended") or moves from one circuit to another in the course of its development.⁸

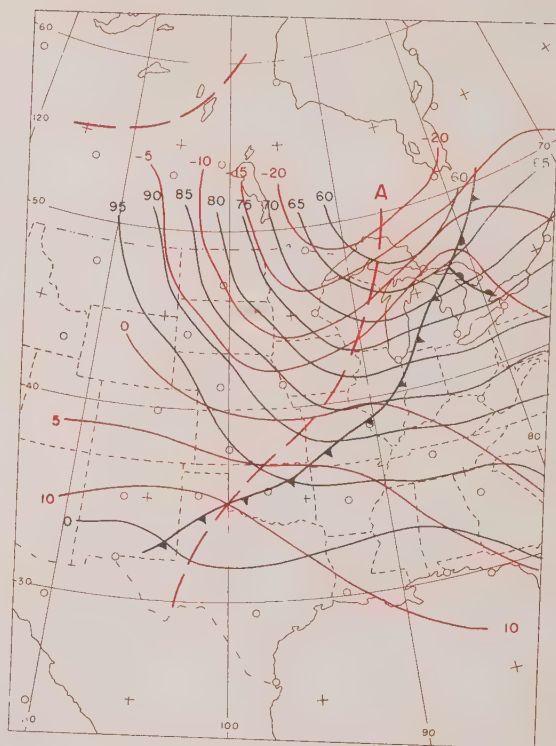
a) Northwest troughs.—Northwest troughs are those oriented approximately NE-SW which are traveling from the northwest in a general northwesterly current. This situation most often occurs over the United States when a

⁷Concerning the possibility of the maximum being at different places on the isobars and on the streamlines see p. 27.

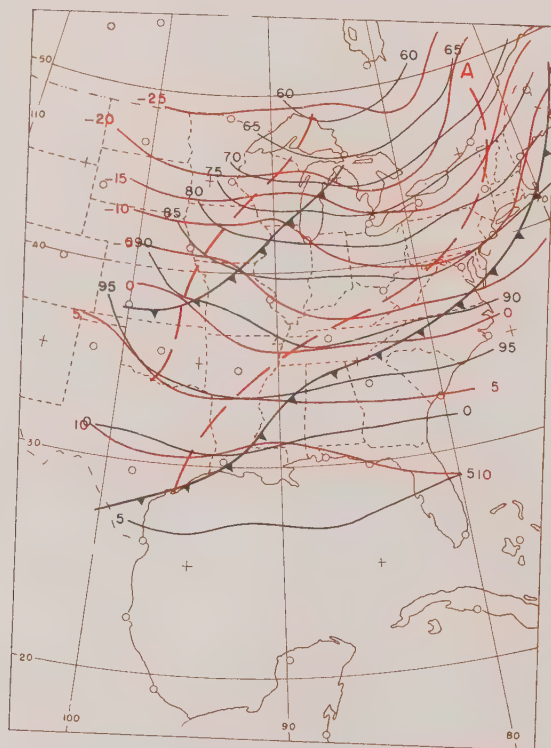
⁸This terminology is introduced by analogy with that used for surface systems in A. J. Henry, E. H. Bowie, H. J. Cox, and H. C. Frankenfield, Weather Forecasting in the United States (Washington: Government Printing Office, 1916).



a) February 26, 1943, 2300 EST.



b) February 27, 1943, 2300 EST.



c) February 28, 1943, 2300 EST.

FIG. 24.—A deepening NW trough (A) at 10,000 feet.

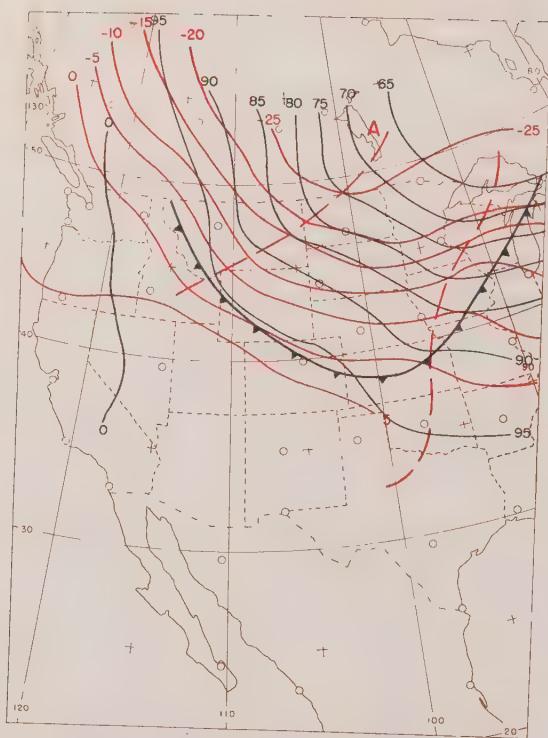
large ridge is located somewhere near the West Coast and the upper winds are between W and NW from the Rockies to the western Great Lakes, but such a NW current with NW troughs traveling in it can occur almost anywhere. Northwest troughs are the most susceptible to deepening, in part, presumably, because of their favorable orientation with respect to the usual cold air supply, though by no means do all of them do so. A typical sequence with a deepening NW trough in February, 1943, is shown in Figure 24, which gives the 10,000-foot isobars in black, the mean isotherms in red, and the surface fronts and 10,000-foot trough lines at 2300 EST on 3 successive days. Note the warm tongue in the mean isotherms a short distance in front of the trough line A and the changes which it undergoes when deepening occurs. This relation of isobars and warm tongue is the usual one for small-trough components,⁹ particularly where a surface front is associated with the upper trough. During the deepening the 24-hour pressure falls aloft become more intense as the trough proceeds toward the southeast and the Polar front swings far south of its normal position for the season; this is a familiar cold-wave sequence.

The deepening of a NW trough will often produce relatively unexpected and surprising results. Depending both on the intensity of blocking to the east and on the spacing and intensity of troughs behind, a strong southwest current may develop ahead of the trough where only west to west-northwest winds were located before (Sept. 24-5 trajectory in Fig. 10), and the rapidity with which a previously rather stable ridge or warm high ahead of the trough may break down when another ridge close in to the west undergoes a strong increase in pressure and extends far north behind the trough, is occasionally remarkable (see maps of April 9-10, 1943, when the distance between the two ridges was about 20° of lat).

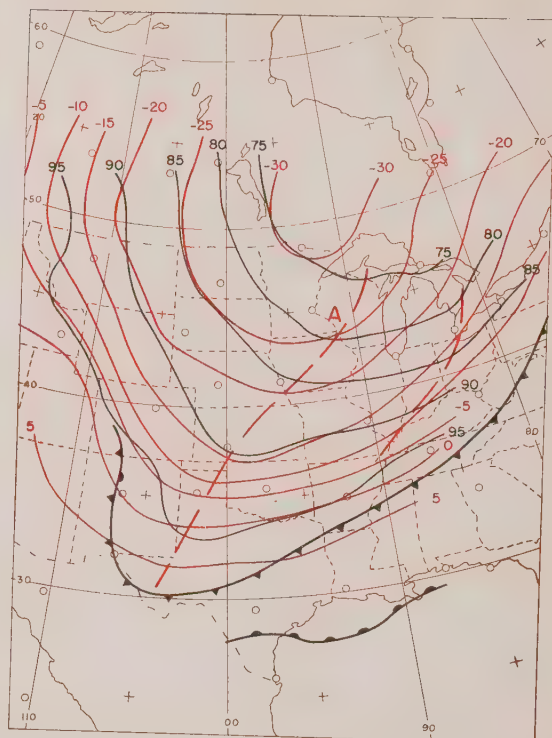
The NW troughs which do not deepen are usually those which have another fairly active trough with large mean temperature rises close-spaced at some 7° to 10° behind and having the mean isotherms "quartering" across the trough itself in the way in which they run through the very slight trough B in Figure 24, instead of forming a warm tongue ahead of the trough. A third type which is susceptible of deepening but more dependent on favorable conditions elsewhere, is shown in Figure 25. The nearest warm tongue in this case is that associated with the trough ahead (this trough sequence goes with Feb. 28-4 in Fig. 10).

Northwest-trough deepening of the type shown in Figure 24 was particularly prevalent during the winter of 1942-43, with the troughs coming

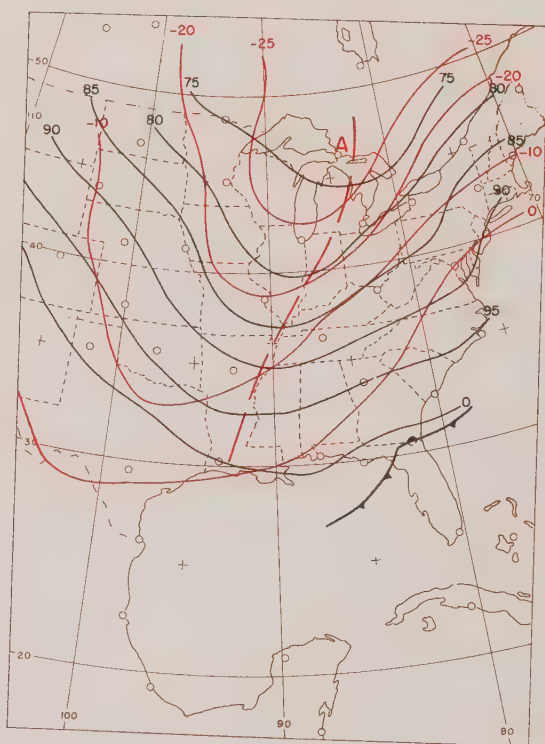
⁹See sec. 3f on mean troughs for definition of "small-trough component."



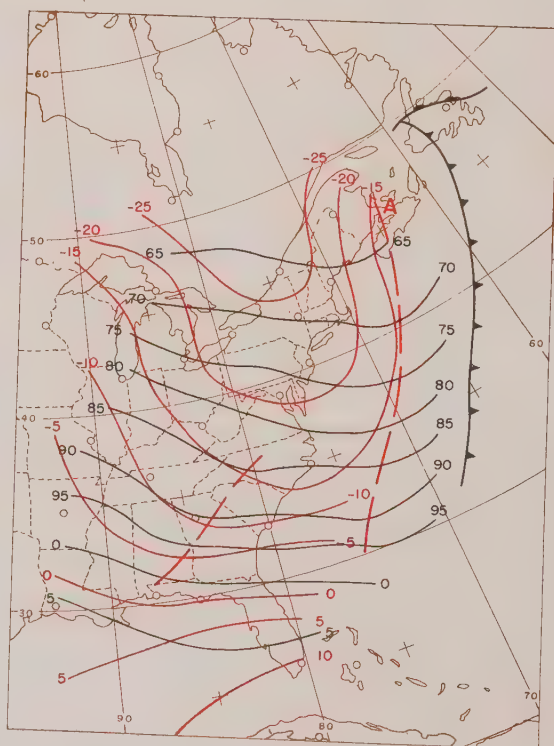
a) February 28, 1943, 2300 EST.



b) March 1, 1943, 2300 EST.



c) March 2, 1943, 2300 EST.



d) March 3, 1943, 2300 EST.

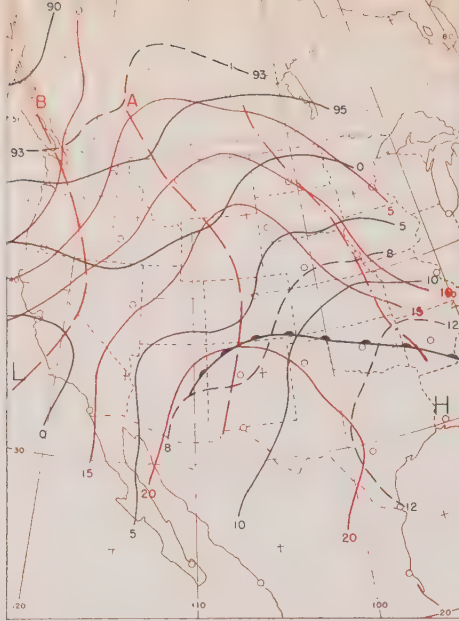
FIG. 25.—Another deepening NW trough (A) at 10,000 feet.

over the ridge either on the northern or, as here, on the arctic circuit and dipping sharply over the Plains into the middle and southern circuits. At the surface in these situations a strong high remains more or less stationary under the extensive 10,000-foot ridge either in the northern and middle Gulf of Alaska, in which case the cold waves sweep the entire United States east of and sometimes even west of the Rockies, or near the Great Basin, in which case the cold waves occur mainly in the eastern and northern United States east of the mountains.¹⁰

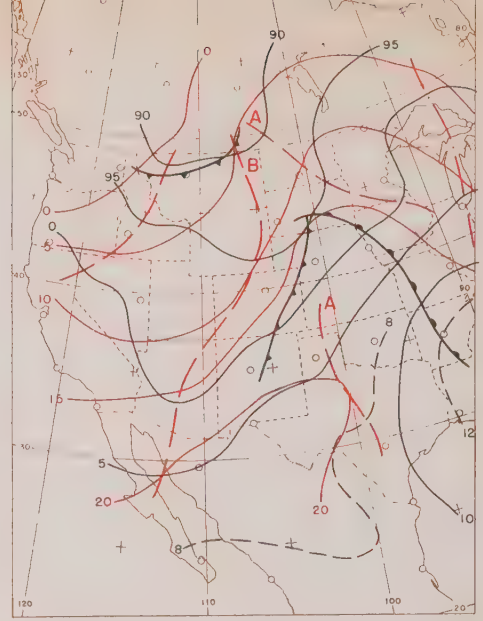
b) Southwest troughs.—These are troughs oriented approximately NW-SE traveling from the southwest in a predominantly southwesterly current. They are generally diminishing troughs in the sense that the velocity shift between the two sides of the trough becomes less and may disappear, but they occur very commonly with two quite opposite sets of pressure sequences. When a strong closed low is forming at 10,000 feet, two or three troughs may become SW troughs, diminish, and disappear during the process while pressures are falling more or less at the same rate all around them. The other case occurs when the 10,000-foot trough is blocked by a persistent or intensifying surface high and upper ridge; here, while the change in form of the trough is about the same as before, the pressures rise around it and the trough fills. On most of our maps these troughs proceeded into the Atlantic beyond the limits of the data before the degeneration process was complete, so that it was impossible to tell whether they disappeared completely or went on over the ridge ahead and down the other side; but it seems likely that both processes occur. This suggests a life-cycle for many of the troughs over the United States—that is, they come in a weakened state over a large persistent ridge in the west, deepen as they move south-eastward as NW troughs, and finally diminish in intensity as they proceed as SW troughs with southwesterly currents¹¹ which may originally have developed when the NW trough deepened. The trough is particularly likely to diminish in this manner if a new and more intense NW trough is already coming down behind it, further intensifying the southwest currents (this is beginning to occur with trough A in Fig. 24). If there happen to be no new troughs coming in, among other possibilities, an essentially new cold trough

¹⁰ These general situations as well as others to be touched on are well described in certain of the weather types set up at the California Institute of Technology (in the present instance, types Bn, Bs, and A). See California Institute of Technology, Synoptic Weather Types of North America (Pasadena, 1943).

¹¹ Much of this classification is merely an extension of the idea stressed by Namias and others that small troughs tend to deepen as they reach the position of a mean trough and fill as they leave.



a) May 3, 1943, 2300 EST.



b) May 4, 1943, 2300 EST.

FIG. 26.—A diminishing and splitting SW trough (A) at 10,000 feet.

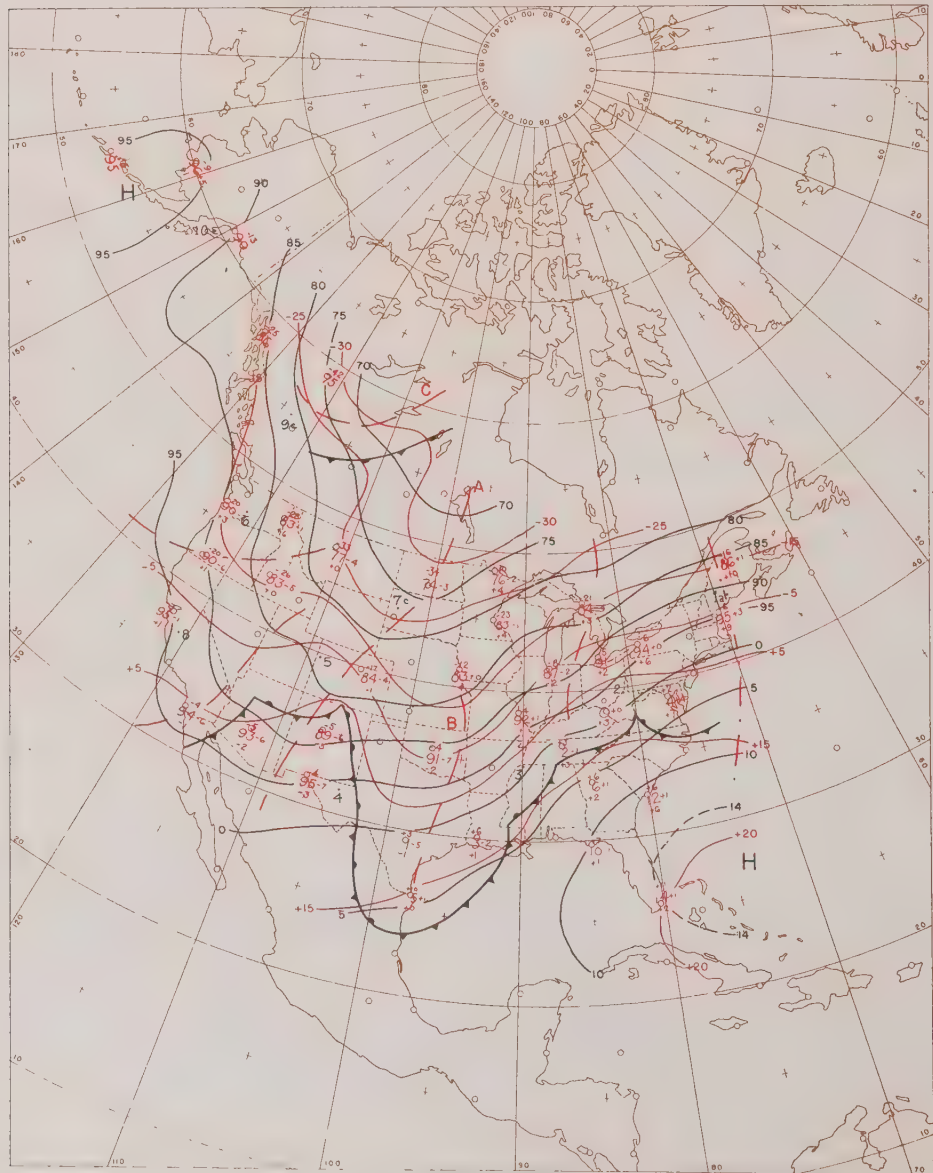


FIG. 27a.—Series with a Wr trough (A) inducing strong deepening 10,000 feet.

with parallel isotherms and isobars which has not moved in from the west may be left behind between the two main ridges as the SW trough moves out.

A type of SW trough action which occasionally occurs is shown in Figure 26, which gives the 10,000-foot charts for May 3 and 4, 1943. Here a closed low at 10,000 feet forms and deepens fairly close to the west of an extended ridge with strong southwest to south winds starting up between the ridge and the low from far down in the southern circuit. Trough A, which is the one in question, is an extended, fairly pronounced trough without, however, any associated surface front on May 3. On May 4, as the upper low (off the map) with trough B deepens, A splits, with one segment moving very weakly along the southern circuit and the other swinging around rapidly as a SW trough to a nearly east-west orientation, and thereafter moving slowly along ahead of the upper low. In this instance the trough lasted for a couple of days after swinging out ahead of the low, but, when the low is deeper with more vigorous currents around it, the trough is usually untraceable the day after it swings out ahead of the low. However, it appears likely that in some circumstances, particularly near the semipermanent lows, the trough may swing completely around the low and come down again on the western side.

c) Wester (Wr) troughs.—The Wester troughs are troughs oriented approximately north-south in a general westerly current and consequently consist of the majority of those observed on normal 10,000-foot maps. They comprise a large and miscellaneous class of troughs about which it is difficult to make a statement having general validity. Troughs passing through the life-cycle mentioned in the last section will be Wester troughs at an intermediate stage in their history, but there are also general map situations in which a Wester (Wr) trough remains such all the way across the United States or in which one that has been a Wr trough for some time becomes a SW trough as it approaches a persistent stable or developing ridge or as deepening of the trough behind it occurs. A large majority of the troughs defined in sections 3d, 3f, and 3g fit into the Wester class, and, consequently, these three sections give mainly a further subdivision of the Westers.

Figure 27 illustrates a deepening situation with Wr troughs that shows one manner in which they can be important. It occurred in January, 1943, under these circumstances: during the process of retrogression of a large, mean trough at 10,000 feet (see sec. 3f) from the East to the mountains, an extensive, deep arctic air mass from Canada and its associated surface high of 1035 mb settled over the northern United States on January 15 and 16, while low pressure conditions prevailed in the vicinity of Colorado

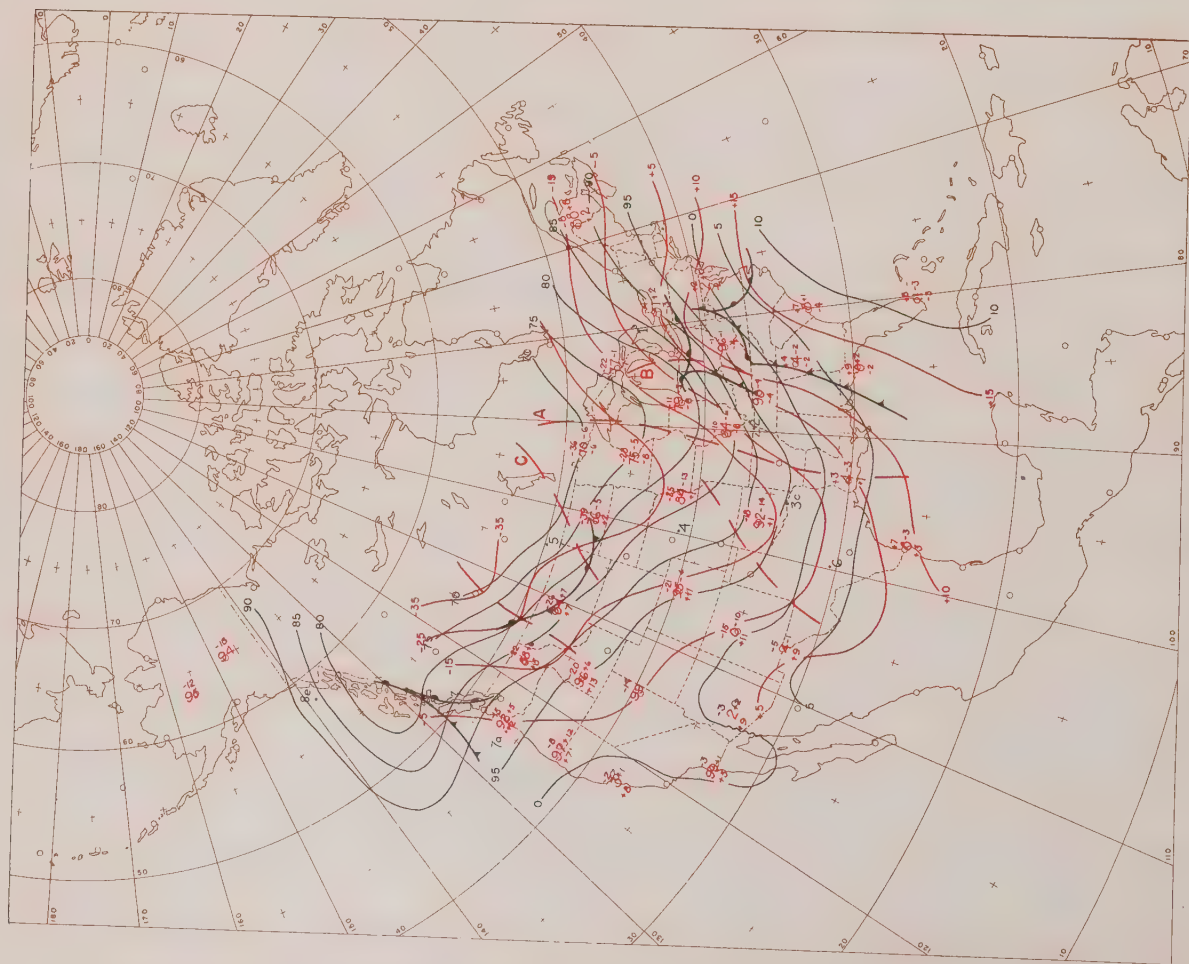


FIG. 27b.—Series with a Wr trough (A) inducing strong deepening. 10,000-foot map for January 18, 1943, 2300 EST.

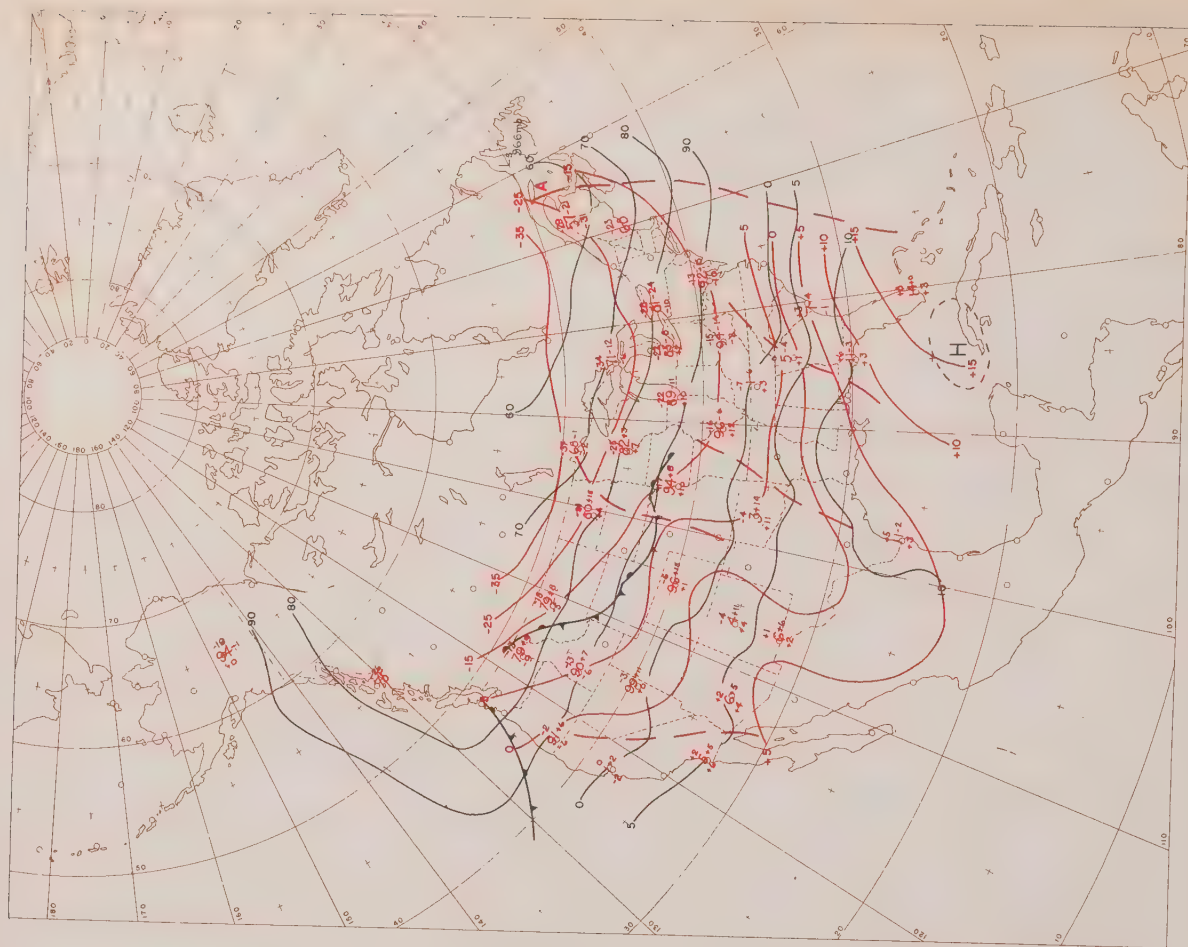


FIG. 27c.—Series with a Wr trough (A) inducing strong deepening. 10,000-foot map for January 19, 1943, 2300 EST.

and in the Southeast.¹² Nothing much occurred toward the development of a strong storm, however, in this potentially dangerous situation until the main Wester trough A caught up with the slowly moving surface frontal system in the Southeast between the 18th and 19th. Then the surface low deepened from 1005 mb in West Virginia to 966 mb in the Straits of Belle Isle, and the Wr trough itself accelerated to 17° of lat per day as it passed the East Coast. As trough A moved east of the mountains between the 17th and 18th, the surface high began sliding from its position just northwest of Lake Superior southward to Nebraska and in so doing displaced the 996-mb low (which had been located in Colorado on the 17th) toward Mexico, where it soon disappeared, while the low farther east, which originally had seemed less active, began deepening. The Wr trough A thus was the key to a forecast of these rather pronounced changes, but it must be emphasized that much depends upon judging the strength of the trough, since two or three milder troughs passed over the surface complex without setting it into motion.

d) High-index (H.I.) and Polar Pacific V-shaped (Pp-V) troughs.—

These are two types, mainly of Wester troughs, which are very typical of high-index maps.¹³ The H.I. trough is one associated with winds which are close to west and which do not shift much more than say, from west to west-southwest on the two sides of the trough; they are also usually of quite strong velocities.¹⁴ H.I. troughs will often in a typical situation come on to the West Coast at approximately 24-hour intervals so that for a time a trough may appear on each daily map at almost the same position. As they proceed across the Middle West, many of them decrease in intensity and,

¹²When giving dates of maps throughout the report, we will refer to the day of the 10,000-foot map at 2300 EST. This will be one day behind the date of the 10,000-foot map on GMT at 0400 and that of the surface map at 0130 EST. Thus the maps of Jan. 15 will be the 10,000-foot map for 2300 EST Jan. 15 and the surface map for 0130 EST Jan. 16.

¹³C.-G. Rossby, Kinematic and Hydrostatic Properties of Certain Long Waves in the Westerlies ("Department of Meteorology, University of Chicago, Miscellaneous Reports," No. 5 [Chicago, 1942]).

¹⁴A few times during the year and also in 1944 we have observed a mild, weather-producing current system coming across a flat, mean ridge in which there is maximum speed of the current to the rear of a line roughly normal to the streamlines and a minimum of speed in front, but in which the streamlines are straight or even slightly anticyclonically curved and have no cyclonic curvature whatever at the line marking the maximum velocity convergence. For discussion of similar systems in the easterlies see H. Riehl, Waves in the Easterlies and the Polar Front in the Tropics ("Department of Meteorology, University of Chicago, Miscellaneous Reports," No. 17 [Chicago, December, 1944]).

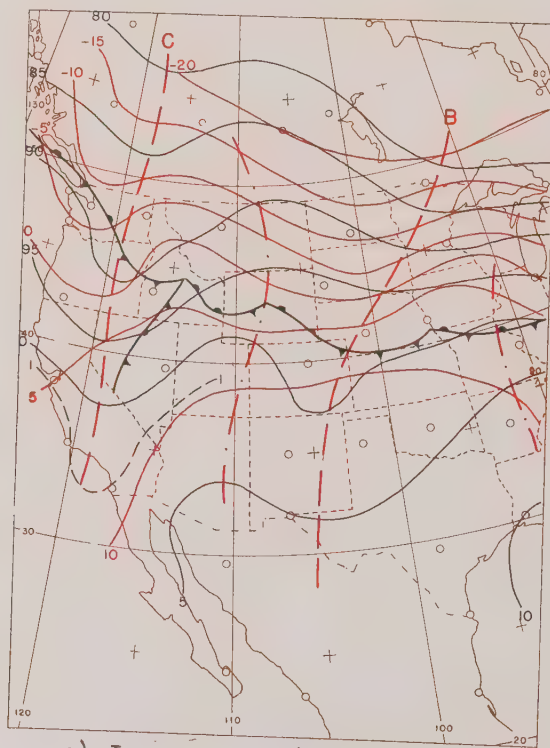
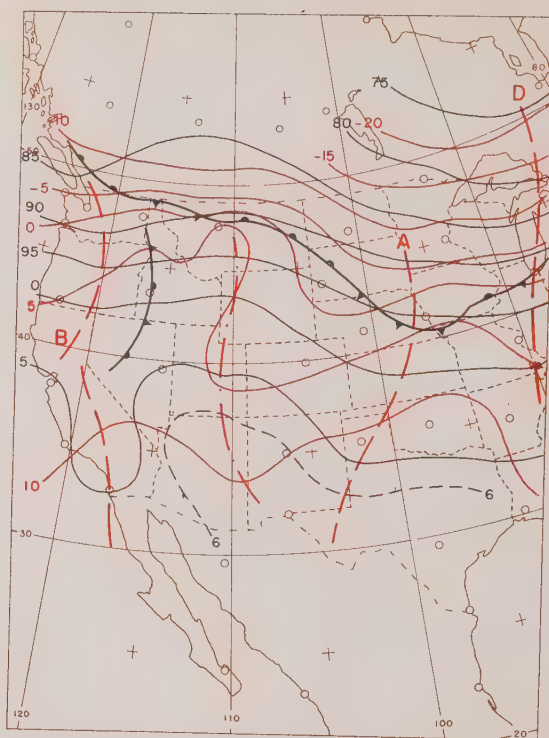
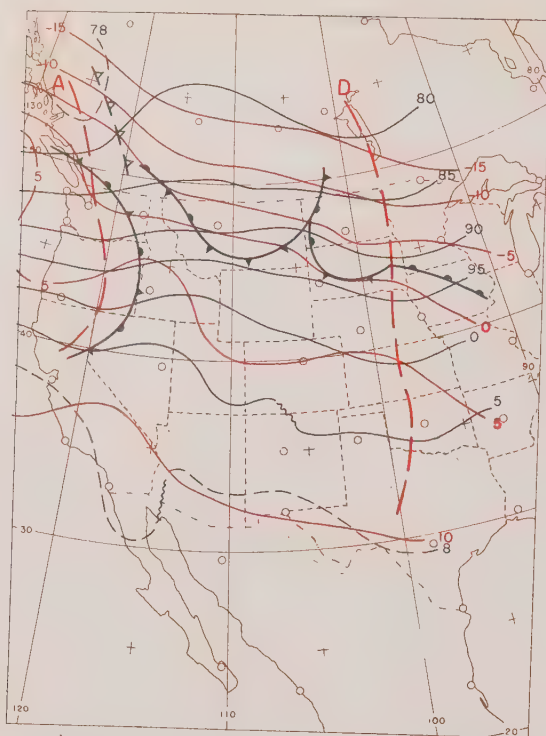


FIG. 28.—Examples of H.I. (A, B) and Pp-V (C) troughs at 10,000 feet.

particularly at the surface, disappear entirely.

The Pp-V trough is again usually a Wester and similar to the H.I. trough but is accentuated in comparison with it to the extent of having a shift in wind direction through the trough from perhaps northwest to southwest. The term "V-shaped" is intended to describe only this greater shift and not necessarily to imply that the pressures in the trough are extremely low. Ordinarily though, a Pp-V trough will have a more intense 24-hour pressure change pattern associated with it than an H.I. trough (in the case below, -5 to -10 mb per day as against -1 to -5 or even slight rises ahead of the H.I. troughs) and, in general, is more likely to lead to developments and shifts toward a lower type of zonal index over the United States.

In Figure 28 troughs A and B are H.I. troughs and C is a Pp-V trough. During the period represented here a series of H.I. troughs came across the country at 10,000 feet, while at the surface a fairly extensive Pc air mass was blocked in the northern part of the country as a number of minor stable waves passed across on the east-west front with the troughs. Finally, after the Pp-V trough came in on January 1, the Pc air began to break toward the south, and by January 3 a deepening, 1002-mb surface low was passing across the East Coast with trough C.

e) Easterly troughs.—Especially in the summertime, troughs moving from west to east in the easterly current below the Bermuda-Azores high-pressure cell will appear on the United States map. There was usually not a great deal of data around them; for a full discussion the reader is referred to the paper by Riehl.¹⁵ Here we shall say only that often the easterly currents (especially to the rear) and the pressure changes associated with them seemed to be more important than the reduced cyclonic curvature that they were able to maintain into the United States (see end of sec. 9a).

f) Mean troughs.—A trough-shaped circulation, usually slow-moving, of fairly large dimensions (wave lengths of the order of 50° of lat at 45° N) is called a "mean trough." Around it move small troughs of the types we have been considering, referred to in this connection as components. In the strongest type of mean trough the component troughs come in from the west as NW troughs and leave in the east as SW troughs, while the position of the larger feature remains relatively unchanged. Less pronounced cases also occur in which the components leave as Westers with almost undiminished intensity, and there are even weaker types. A line was not actually drawn to indicate the mean trough, since one of the components is usually fairly close to the

¹⁵Ibid.

center, but it would correspond, if drawn, to the trough line indicated on a 5-day mean pressure map or similar chart.¹⁶ Particularly in the well-developed cases it is helpful to think about the mean trough. For example, in these circumstances consideration of only the trough components might lead to a forecast of a 10,000-foot wind-shift to northwest at a position ahead of one component as it passed, whereas actually the winds would stay near southwest as another component dropped down into the mean trough. Also, certain large-scale processes taking place over several days can often be recognized even on the daily charts, by considering explicitly the behavior of the mean trough (see sec. 9).

g) Cold troughs.—The cold trough corresponds ideally to the case of parallel isotherms and isobars discussed in section 2, chapter I, but it occurred in a clear-cut fashion only once or twice during the year. Usually a large trough which might superficially appear to be a cold stationary trough would be found on close examination to be in fact a mean trough with a new trough component at the position of the mean trough on each day and the old components moving on out toward the east. The particular situations which most nearly approached parallelism of isobars and isotherms all through the trough (Nov. 23 and Dec. 28) occurred with troughs on the southern circuit extending from moderately vigorous, closed 10,000-foot lows at 35° to 40° N. There was a slowly moving surface cold front with each trough which was located abnormally far ahead (6° to 7°) of the trough. From the analysis described in chapter II we should expect such a trough to remain stationary, and the observed cases bore this out at least to the extent that the troughs moved only 3° or 4° lat or less per day despite the considerable force of the winds.

h) Closed lows (at 10,000 feet).—Very frequently, in one part or another of the United States map, the forecaster is confronted with the necessity of anticipating the behavior of closed low circulations on the 10,000-foot chart. This is a problem which changes complexion radically with the season; in general, the likelihood that a system, once it is closed aloft, will end as a deep one with strong weather changes, is much greater in the cold season than in the warm season. In the late spring and summer, even after a low has become closed aloft, it is by no means certain that it will deepen further or become a very strong storm, while in the winter, especially for a low north of the southern circuit, this is an

¹⁶J. Namias, Methods of Extended Forecasting (Washington, D.C.: U.S. Weather Bureau, September, 1943).

extremely likely eventuality. Such 10,000-foot lows as came within the field of our maps may be divided roughly into three categories (not necessarily mutually exclusive): active extratropical lows in the middle or northern circuits, in some stage of development from deepening to stagnation or disappearance into one of the semipermanent centers; subtropic lows below latitude 40° N, with rather sluggish circulation, many of which do not deepen; and hurricane centers.

Three particular considerations which have seemed useful in the problem of forecasting upper closed lows will be described first, two of them depending upon certain trough sequences and the other upon pressure rises to the west of the forming low.

Extratropical upper lows form over the United States frequently after the surface systems have been at the point of deepening for some time; for example, a low complex with small waves may be present in the Southeast (as in Fig. 27), or a surface low may be lingering in Colorado on the slope of the Rockies. Deepening will finally occur when an active Pp or Wr trough with definite pressure rises at the surface overtakes the relatively mild trough which happens to be passing across the surface system at the time (often a number of troughs, H.I. in form, will pass over without moving the surface low but only causing small waves on the semistationary front between the Tg or Ta and the Pc air). The surface low starts to move out and deepen as the upper low forms, and the horizontal distance between the two decreases as the whole system approaches the condition of a cold low. Depending upon the intensity of blocking from the Atlantic high, the 10,000-foot low will either move northeastward and out past Caribou, Maine, or more nearly due northward into the Hudson Bay region, where it finally stagnates or disappears. Once the extratropical 10,000-foot low has formed and attained considerable intensity, a NW trough dropping down into it with a secondary cold front and vigorous mean temperature falls will usually redouble the deepening.¹⁷

A second process which at least twice during the year resulted in the formation of a strong extratropical low is illustrated in Figure 29. Based on these two cases and on our evaluation of some of the probably pertinent factors, the following hypothesis is offered. When a moderately active trough or subtropic upper low (persistent 24-hour fall of 1 to 5 mb or more) has remained in the Southwest (Arizona and Southern California) for

¹⁷J. Bjerknes and H. Solberg, "Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation," Geof. Publik., Vol. III (1926).

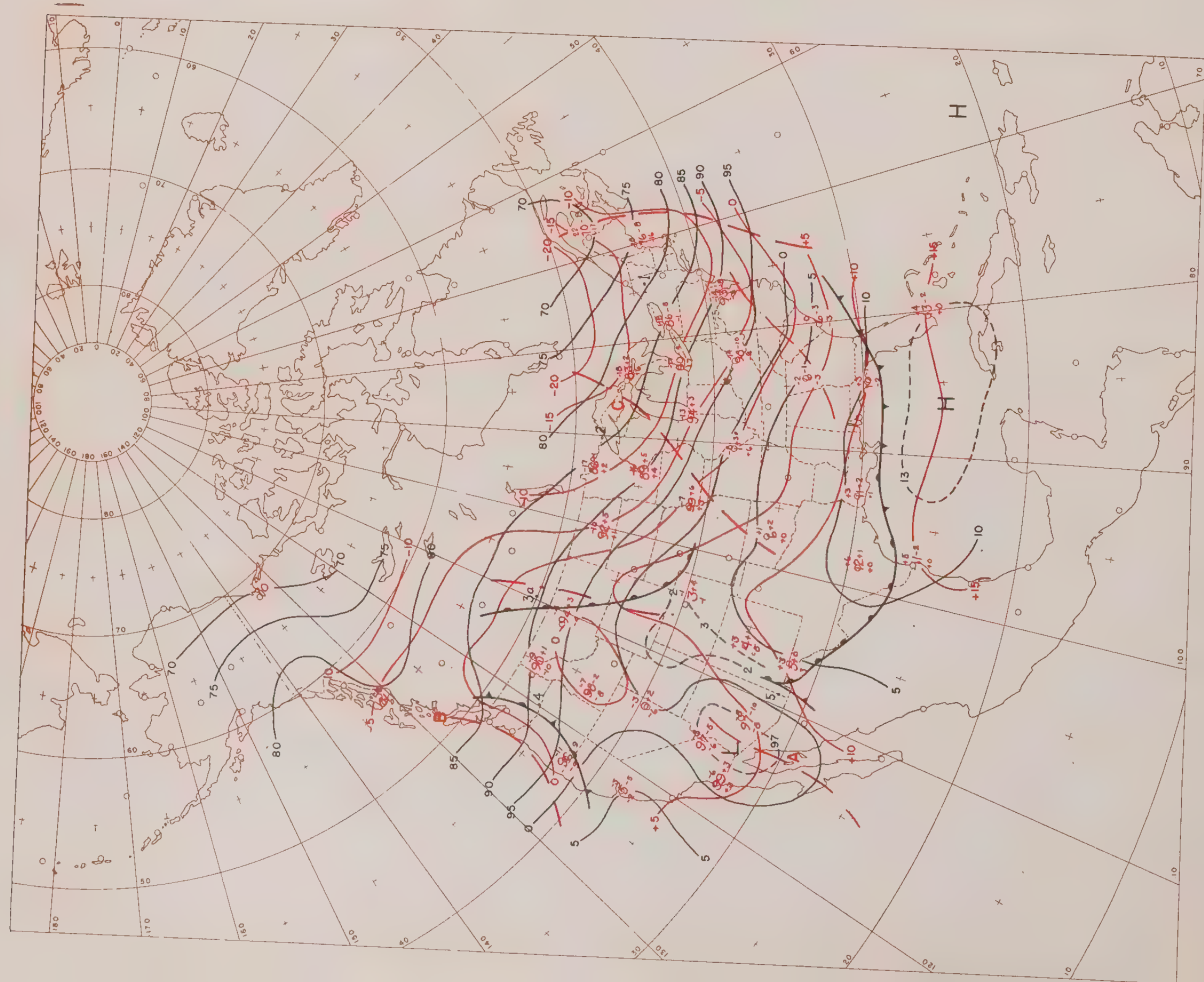


FIG. 29a.—Series showing picking-up of a small South-west low by a Pp trough (B). 10,000-foot map for February 1, 1943, 2300 EST.

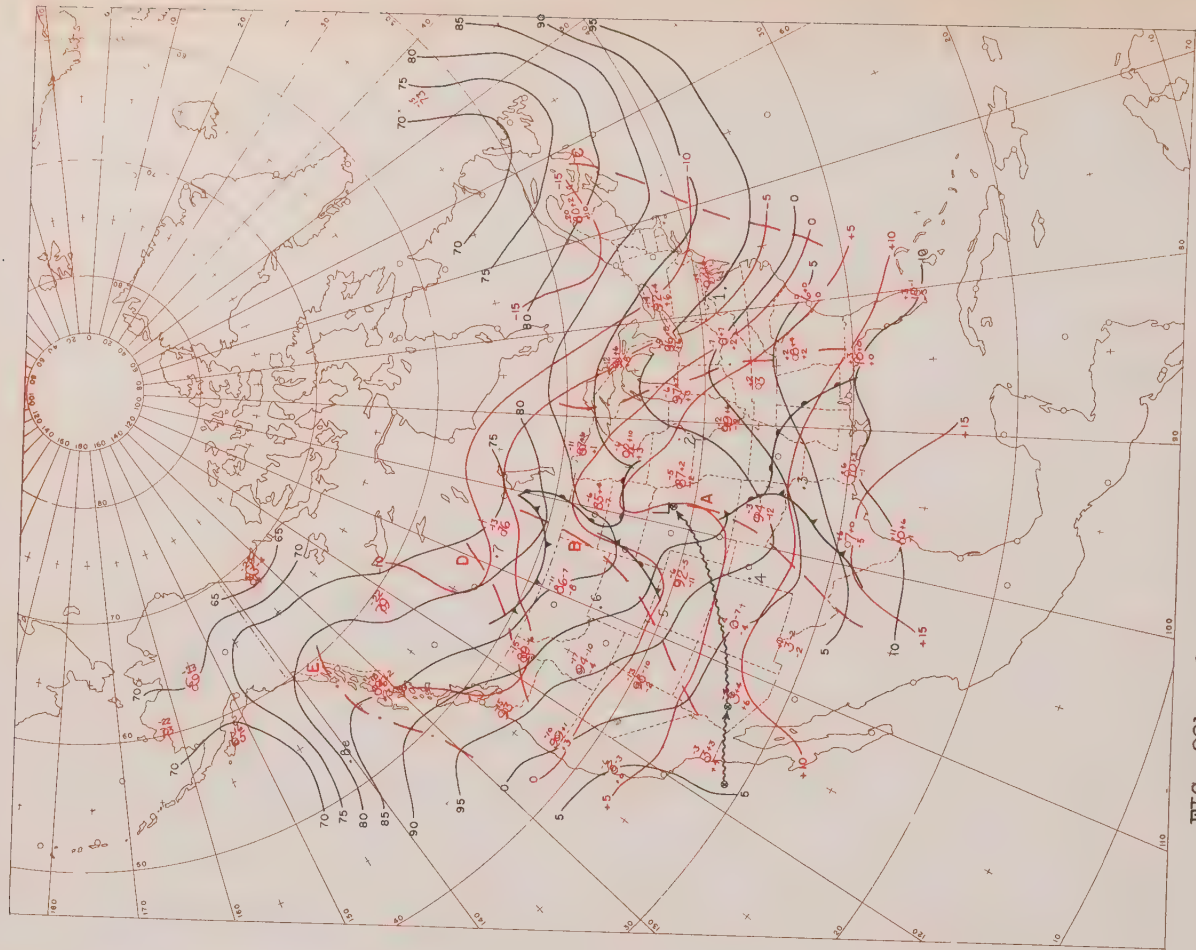


FIG. 29b.—Series showing picking-up of a small South-west low by a Pp trough (B). 10,000-foot map for February 2, 1943, 2300 EST.

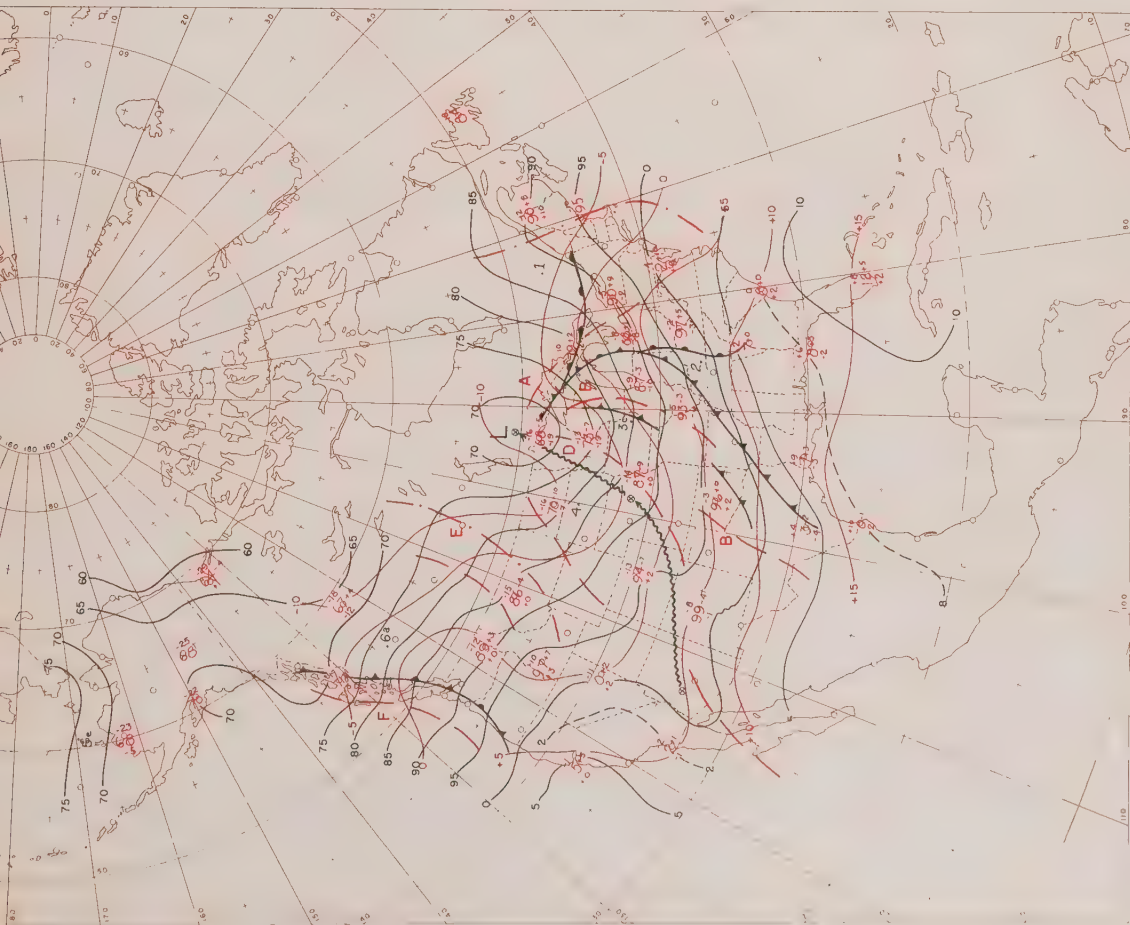


FIG. 29c.—Series showing picking-up of a small South-west low by a Pp trough (B). 10,000-foot map for February 3, 1943, 2300 EST.

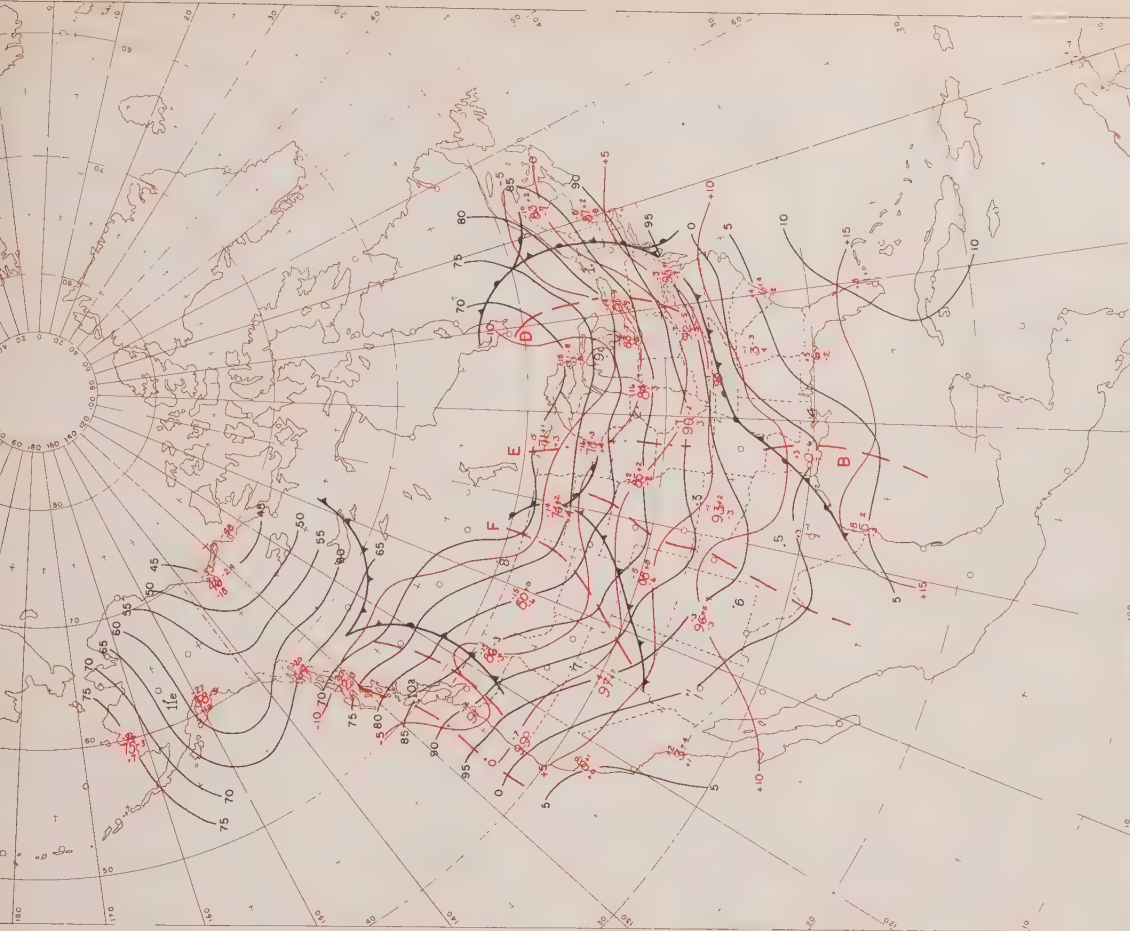


FIG. 29d.—Series showing picking-up of a small South-west low by a Pp trough (B). 10,000-foot map for February 4, 1943, 2300 EST.

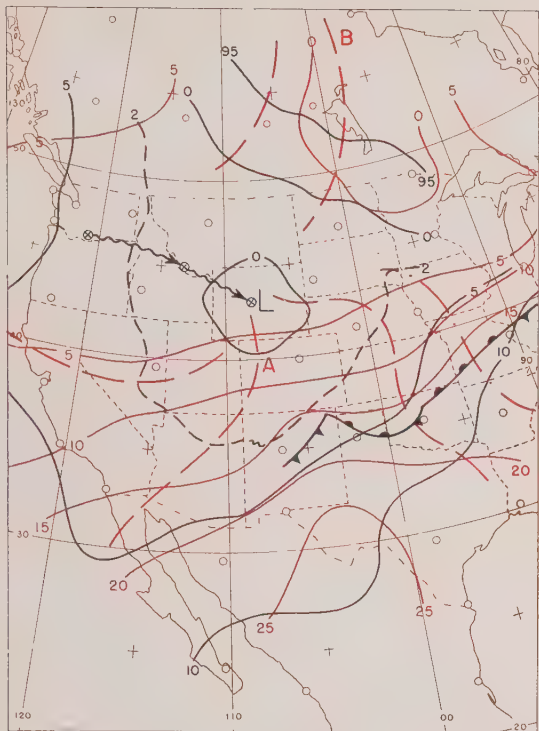
a day or more, an active (-10 mb/24-hr change) Pp trough arriving on the middle circuit at a spacing of about 10° from the trough in the Southwest will, when the ridge between is not pronounced, move it rapidly (13° lat or more per day) northeast and north, with a strong surface and upper center developing by the second day in the central United States and Canada.¹⁸

The third sequence brings about either the entrance into the United States of an upper low which has been moving slowly along in the Gulf of Alaska or the formation of a new low, as a strong pressure rise which seems to come from the southwest builds up the ridge behind the low or trough and initiates north or even northeast winds on its eastern side. This accompanies the development of the new low or, where the low is already present, accelerates it rapidly across the coast line. The SW pressure rise in the Gulf may be fairly restricted in dimensions, as is the case on occasion when a subtropic low is formed over the West by a pressure rise developing ahead of another low which is deepening out over the Pacific Ocean, with its trough spaced 17° or more from the continental trough. In these cases it is sometimes possible from the coastal reports at the surface and 10,000 feet to have a clear enough picture of what is occurring in the Gulf to be able to anticipate the formation of the 10,000-foot low over the land. In other cases the SW pressure rise may spread over the whole western and central Gulf of Alaska, building the ridge far into the north and shunting onto the continent any trough or low-pressure activity of the Aleutian Low which may be in the eastern and middle Gulf. When this occurs and the Aleutian upper low is shifted bodily into the United States or Canada, very strong changes both in the patterns and in the associated weather elements should normally be expected.

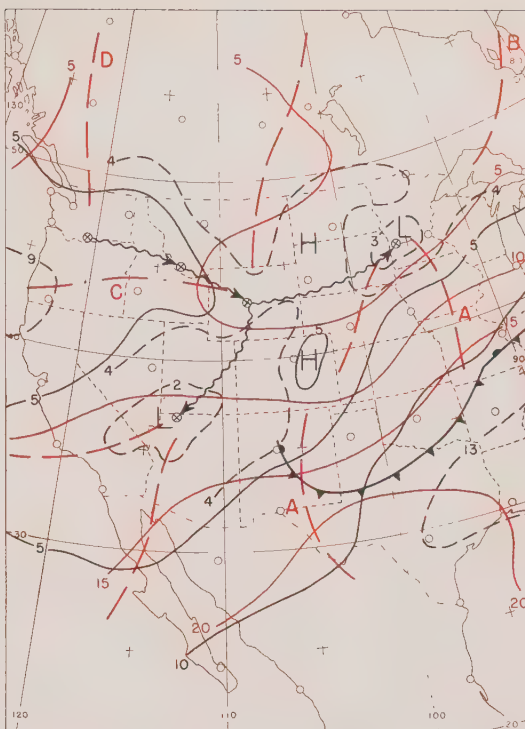
Around Nov. 21, Dec. 27, Mar. 15, and May 24, 10,000-foot lows coming across the United States followed a track approaching the symmetry of that for the low of Mar. 24 in Figure 20. The low comes in rapidly, then slows up for 2 or 3 days between 90° and 100° W, and finally accelerates rapidly out past the East Coast, where in some cases it seems to find renewed sources of energy while in others it weakens. The positions of the upper low are occasionally strikingly close to being symmetrical about the meridian through the point of slowest movement, and, though this is by no means certain to occur, it may be a considerable aid if detected in about midpassage or before.

Subtropic lows are most frequently encountered on the United States

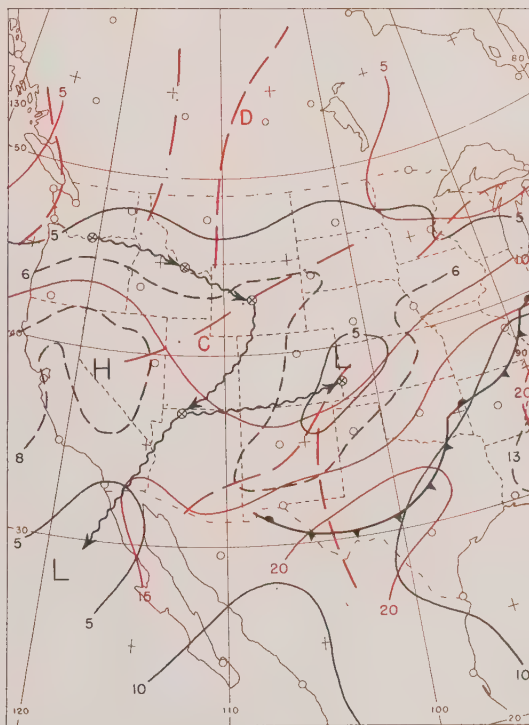
¹⁸ Later evidence suggests that the general idea here is definitely useful also in other regions and in less pronounced cases (e.g., July 25-26, 1944).



a) May 16, 1943, 2300 EST.



b) May 17, 1943, 2300 EST.



c) May 18, 1943, 2300 EST.

FIG. 30.—Splitting of a subtropic 10,000-foot low.

map in the Southwest and over the ocean off San Diego, where they may be quite persistent. At San Diego they either move in from the west or move out from the continent; this latter case occurs mainly when a SW pressure rise builds a ridge in the ocean particularly strongly toward the north and northeast, developing northeast winds on the forward side of the ridge, and moving the upper low out from the continent toward the southwest. In the cold season when this takes place, usually the whole low moves across the coast, but in the summer and the warmer parts of the transition seasons the splitting process depicted in Figure 30 often occurs. One not very active low continues on eastward, frequently diminishing to a trough a short time later, and the other moves southwestward beyond San Diego, with very little if any weather associated with it so far as one can tell from the surface chart.

The interaction of upper lows with the troughs and currents surrounding them was most often seen on the maps when subtropic lows and Pp flow with H.I.-like troughs were involved. The selection of these interactions given below is most immediately derived from these cases but is thought likely to apply in perhaps modified form to other types of lows and currents. Out of the numerous possible variations, the following general types have seemed most important:

1. If the axis of Pp flow¹⁹ is oriented so that the probable trajectory of the flow takes it into the rear quadrant of the low with the trough in it becoming a NW trough, accelerated movement for a time and deepening of the low is the usual result.
2. If the ridge between the Pp trough and the low is moderately pronounced and the axis of flow is well north of the low, the trough and its current can go across the outlet of the low into the north preventing deepening and finally reducing the low to a trough. (It is also possible for the trough and current to split, one branch dropping into the low and one going across above. Depending on the relative strength of the two branches, the low can deepen momentarily and then fill to a trough or can deepen sufficiently to be able to resist the filling tendency.) See p. 45.
3. The low may be strong enough when a Pp current cuts across to the north not to dissolve completely, but any deepening will be retarded. The effect on the Pp trough and current in this instance is to retard them.
4. If the ridge between the Pp trough and the low is weak and the

¹⁹"Axis of flow" refers to a line parallel to the current drawn roughly along the zone of velocity maximum or near the center where the speed is close to uniform across the stream.

axis of flow lies not too far north of the low, the trough may overtake the low and amalgamate with it as the spacing becomes less than 10° , with ensuing moderate to strong deepening (the case of Fig. 29).

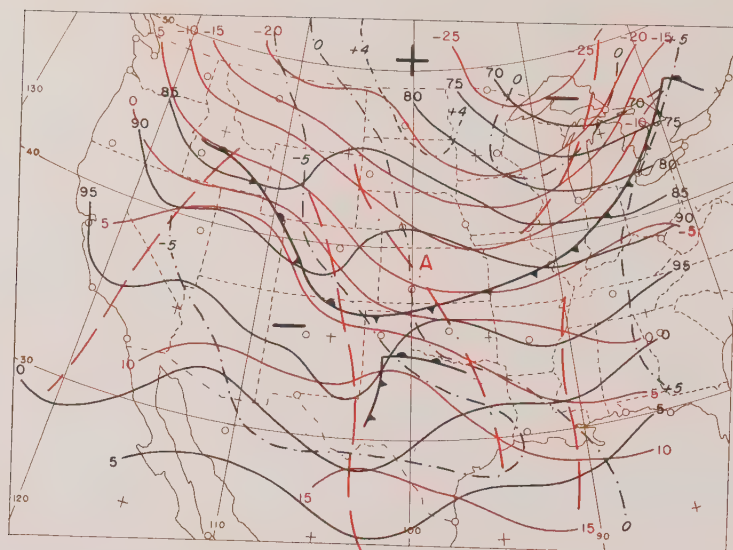
5. If the ridge between the low and the trough is pronounced with the Pp trough vigorous, intensifying, and well to the west, a SW pressure rise can develop, building the ridge and being followed by deepening of the upper low east of the ridge.

Not much will be said of the hurricane lows which drift into the United States in the summer and fall in the easterlies below the Atlantic high, except to state two observations which in part also apply to some subtropic lows. First, particularly when the storm is a mature one, it may persist for some time after entering the continent. Even after the surface low has to all appearances filled completely, an upper circulation may persist and be accompanied by more than ordinarily showery weather. Second, pressure-rise areas from the west which are centered well to the north, yet which might at first sight appear capable of moving the low on eastward, can go through to the north without doing so. Small, closed 10,000-foot highs can even form north of the low and move eastward while the low drifts erratically toward the west or southwest. This occurs fairly often with subtropic lows (see Fig. 40), and the difference between rises which thus pass across to the north and those which move and deepen the low, is similar to that between the situations in paragraphs 2, and 4 or 5, respectively, above.

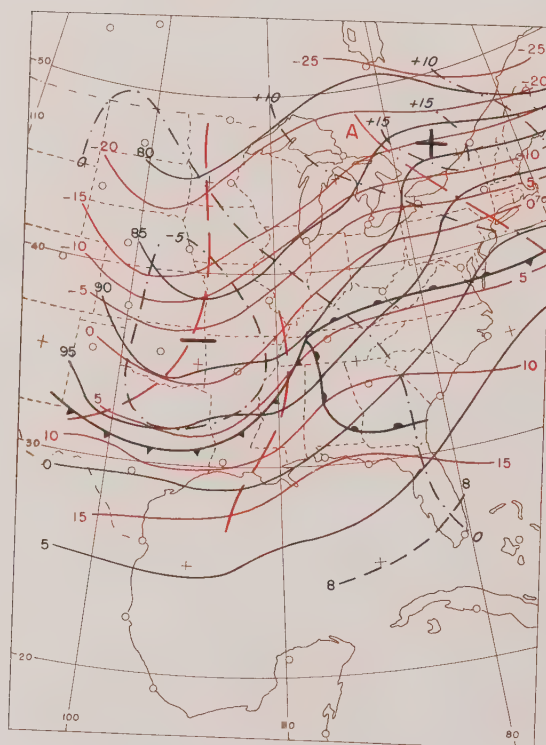
4. Ridges

One of the particulars which has gradually impressed us as of the utmost importance to consider in making a forecast for the regions on our map, especially any very long-range forecast, is the question of the position, extent, intensity, and the nature of the changes going on in the major ridges on the 10,000-foot map. Certain of these are extremely stable features and often provide the best starting-point from which to build the forecast. The most important types from this standpoint are the mean and extended ridges and the closed highs; the SW and NW ridges described first are most often of the nature of ridge components, although usually they give important indications with respect to the larger features.

a) Southwest ridges.—As in the case of troughs these are ridges extending roughly NW-SE with a mean direction of flow of the surrounding currents from the southwest. As a class they tend to undergo intensification and to be associated with increasing pressure-rise areas, although, as



a) March 4, 1943, 2300 EST.



b) March 5, 1943, 2300 EST.

FIG. 31.—A strengthening SW ridge (A) at 10,000 feet.

always, the degree to which this occurs depends upon a number of other circumstances. A fairly typical SW ridge occurs in the situation given in Figure 31. When a deepening trough complex is located close to the west with the major 10,000-foot current (see sec. 9b) from the SW, as in this case, the ridge is likely to move unexpectedly rapidly for a time until the "spacing" and intensity of the ridge have become better adjusted to the changed conditions. This usually means that after a while the ridge becomes a large mean ridge connected with a stable surface high and with SW troughs going over it. (A less frequent alternative when the pressure falls extend far south and the surface low does not move north immediately is that the ridge becomes an extended, moving ridge preserving its identity from day to day, i.e., not having the mean character with small components passing over it.) Note that not until the 5th has the ridge developed to the stage where it completely satisfies the definition of a SW ridge. As a matter of fact, few SW ridges satisfy the definitions as typically as do a good number of NW troughs. Often the ridge is not located between WSW winds in front and SSW or S winds to the rear, as would be ideal, but between W or even WNW winds and SW to SSW winds; since otherwise they fit into the group very well, these will be called SW ridges.

The type of SW ridge shown in the figure is associated with very strong weather of typical warm-front type. The ridge line on the prognostic chart is consequently particularly useful in the forecast, since the precipitation does not normally start at a given spot until soon after the ridge line has passed. (This is not invariable, however, and if the SW ridge line is not too strongly pronounced, the precipitation may extend ahead of the ridge line. In one case around Dec. 28 involving a low in the East with a complex set of fronts the precipitation extended for a time 7° ahead of the ridge line, but so great an extension is quite unusual.)

b) Northwest ridges.—In Figure 32 is shown a sequence which is fairly typical of some NW ridges.²⁰ These, starting with a NE-SW orientation, tend to decrease in intensity as they move southeastward but may, as in this example, be still sufficiently strong to turn the corner at the bottom and continue on their way. Here the surface chart would have been of particular help in foreseeing that the ridge would be able to continue toward the east. On the 6th a slowly moving polar high of 1035 mb with north-south axis was located at the 95th meridian, and when the upper ridge came down it connected with this surface feature, which then began to move

²⁰This is the ridge with point Mar. 6-4 in Fig. 12.

off eastward and increased to 1044 mb; at the same time the pressures in the 10,000-foot ridge also began increasing.

If there is a strong, mean trough type of circulation to the east, the NW ridge is likely to disappear completely by the time it should have reached the bottom of the mean trough. The exceptions to this occur mainly when a strong, deepening NW trough comes down behind the ridge component, which then begins to acquire some of the characteristics of a SW ridge.

A third possibility, among others, which mainly occurs around a closed 10,000-foot high and with rather small component ridges is that the ridge swings around to an east-west orientation and becomes almost stationary between westerlies to the north and easterly winds to the south.

c) Mean ridges.—Even more frequently than in the case of troughs, a large ridge in the 10,000-foot circulation may persist in the same general location for considerable periods of time without extensive changes in its form, while small troughs and ridges go over it. (Usually there are more of the former, since some troughs are so close together or so formed that there is no maximum of anticyclonic curvature or sometimes even no anticyclonic curvature between them.) The form of such a mean ridge may range all the way from that of the rather flat, wide ridges which are common during H.I. conditions to one so accentuated in north-south extent that trough components are hardly able to persist while going over; the mean ridge then approaches the character of an extended ridge. The process of going across the ridge will be associated with changes in the characteristics and intensities of the smaller features—e.g., from SW troughs to NW troughs, etc.

An example of the forecasting importance of the ridges is associated with the problem of forecasting polar outbreaks and cold waves over the United States. Consider a typical H.I. situation that has prevailed for some time with a flat mean ridge at 10,000 feet near or just off the West Coast and the Pc air over the continent confined above a more or less east-west boundary near the Canadian-United States border. What seemed to us often to be an important requisite for the onset of a lower index over the United States with outbreaks of Pc air into southerly latitudes was the development of a stronger, more accentuated ridge in the middle or western Gulf of Alaska to the west of the previous position of the mean ridge. As this occurred, a Pp-V trough might come in at the coast followed by a succession of NW troughs coming down from Alaska and successive polar outbreaks into the United States. A number of times it was also our impression that the SW pressure rise which built up the western ridge was associated with a

deepening low system even farther west out over the western Pacific (see the extreme case in the Aleutians on May 22), so that a 1- or 2-day forecast of exactly when breakdown of the high index in the United States might be expected depended to a considerable extent upon knowing or guessing what was likely to happen to the ridge in the Gulf of Alaska, which in turn was conditioned by the situation over the far west Pacific. It is not intended to imply that this is the only or even the principal sequence involved in the cold wave problem, although usually the ridge idea has turned up in our attempts to find the necessary prior conditions. Further examples of such large-scale relations are discussed in section 9.

d) Extended ridges.—A ridge which extends far across two or more circuits with a strong wind-direction contrast between the two sides is designated an "extended" ridge. The movement of a ridge so designated should also, unlike that of a mean ridge, be a bodily one and not accomplished by maximum development of small components at successive positions. The major problem when the forecaster is confronted with such a feature on the map is usually to determine just how much stalling effect it is going to have on the general movement of surrounding systems. Since such a ridge is also usually associated with a surface high, this corresponds to a surface problem of just when and how rapidly the high is going to move.

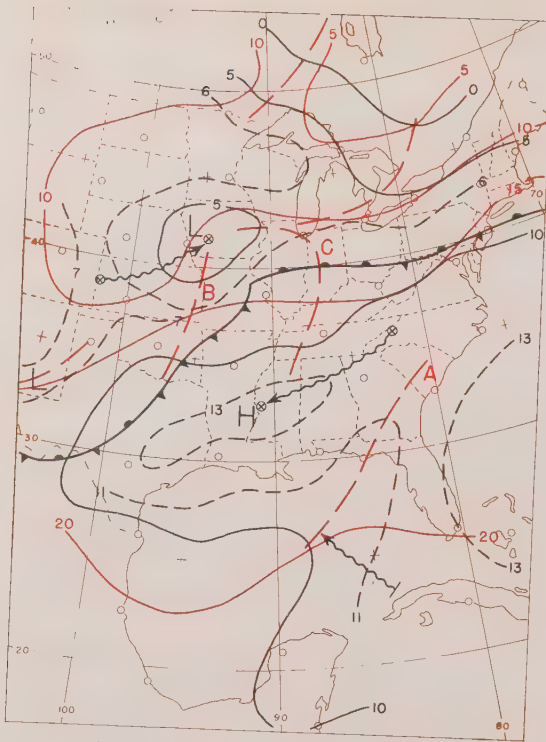
One factor which has some bearing on this problem of movement is connected with a strong NW polar flow on the forward side of the extended ridge. Such a flow, if extensive, vigorous, and constantly renewed, will have a distinct stalling effect on the ridge, holding it down to a movement of only a few degrees of latitude per day. The way in which this works may be illustrated by discussing the problem as it occurs fairly often in the eastern United States. Suppose we have an extended ridge running from the southern up into the northern circuit moving eastward across the western Great Lakes with an associated moving surface high. In such a case the normal expectation would be for the ridge to move eastward at the usual rate and the pressures at a station such as Caribou, Maine, to begin to rise at the surface and aloft. But if a strong NW flow prevails across the East and a NW trough, perhaps with a secondary cold front, slips down out of Canada, the pressure at Caribou, instead of rising, may drop very sharply, along with a strong fall in the mean temperature, while the ridge is held down to a movement of only 3° or 4° lat per day. Later, unless the same thing happens again, the pressure will rise strongly at Caribou, and the ridge will pass on across the coast. (This particular case of the NW trough at Caribou has caught us unawares a number of times on the forecast.) The presence of a deepening

trough complex and strong SW currents close in to the west of the extended ridge will tend to operate in the opposite direction, moving the ridge and its attendant pressure rises right along. If, however, the deepening goes far enough and the 10,000-foot currents swing into south or even farther, the whole situation will tend to approach stagnation. Sometimes quite a delicate balance is struck here between the two influences, and, when the stalled ridge finally breaks loose, it may move toward the east with unexpected rapidity.

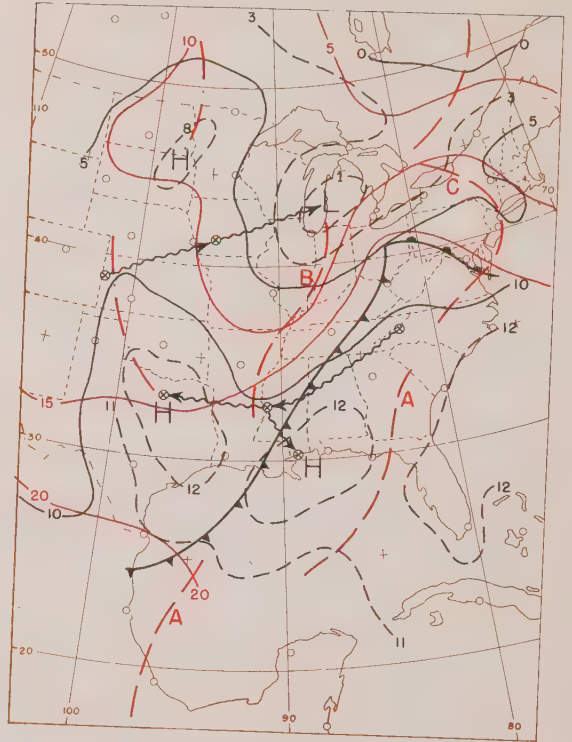
At the West Coast one can sometimes tell when an accentuated mean ridge is going to start moving as an extended ridge by watching the 24-hour 10,000-foot pressure changes, which in such cases will show the pressure fall extending far south into the southern circuit. When the ridge has definitely started to move, it is also usually the case that the first few troughs behind it are not exceptionally strong, the first vigorous and deep W_r trough being in the second or third place in the series.

When an extended ridge stretches exceptionally far into the north, it is possible for it to behave as a mean ridge on the middle circuit, with small troughs going over it, while the section in the northern and arctic circuits continues to move as an extended ridge. (This is frequent with closed upper highs in the north, for which see the next section.) It can occur either in such a way that the general ridge character of the flow is not much disturbed in the mean section or so that the southern portion of the ridge is completely replaced on one day by a strong V-shaped trough followed by the re-establishment of the extended ridge all the way through on the next day as the strong trough moves on. A further similar case occurs on the middle and southern circuits in which a strong westerly circulation with P_p type troughs on the middle circuit moves the northern half of the ridge along without very much affecting the southern portion.

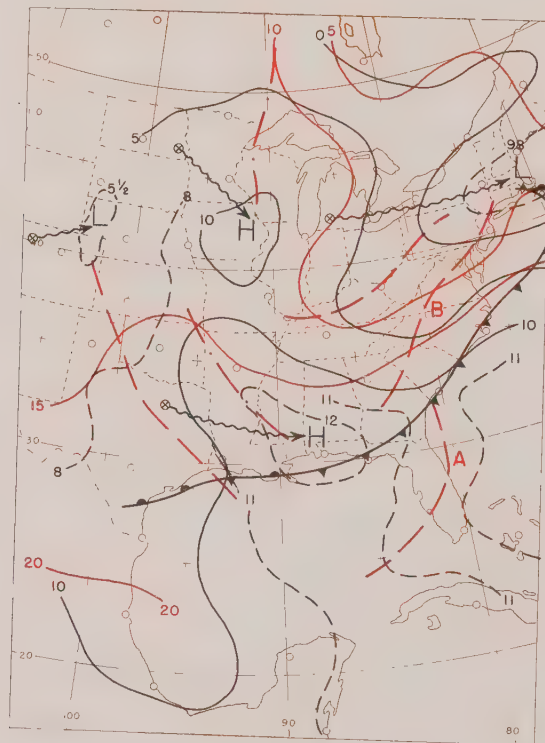
e) Closed highs (at 10,000 feet).—Closed highs at the 10,000-foot level are a quite common feature of usually considerable persistence, particularly in the summertime. Even in the cold season there are long periods when closed highs other than the normal subtropical cells are present over far northern and middle latitudes. The problem of forecasting the formation and the oscillations in intensity, together with the movements of upper highs, is one to which we have noticed no outstanding answers. We shall describe here several processes which may serve to increase familiarity with the idiosyncrasies of such highs, but, though many of the ideas which we have given or will give are often applicable to the problem, we were not able to avoid frequent error in forecasts involving these features.



a) May 19, 1943, 2300 EST.



b) May 20, 1943, 2300 EST.



c) May 21, 1943, 2300 EST.

FIG. 33.—A closed high at 10,000 feet moving westward past a surface front.

Many of the relatively small highs (i.e., not the subtropical cells) which we could observe were very persistent and therefore of considerable value in forecasting. (There were a few cases of very small upper highs which seemed to be almost entirely shearing phenomena between two currents and were quite unstable, lasting only for a day or so.) Depending upon the general situation, these upper highs were usually either relatively stationary in the region of a mean ridge or moving fairly regularly toward the east in association with an extended ridge, the latter being often the case with cells moving along the southern circuit from northern Mexico to Florida, associated with an extended ridge running up into the northern circuit. But there are cases, one of which is given in Figure 33, in which the high either moves from the east as a consequence of an impulse in the easterlies or fades westward into a ridge as NW troughs come down on its eastern side (see p. 19). The case in the figure is one in which some kind of easterly impulse, represented by the easterly trough A, seems to be responsible for the westward movement. Note here how the surface front to the west, which ordinarily would be expected to be stalled by the high, passes on east underneath it. The high splits with the cell behind the front developing and then moving eastward, while that to the east disappears. Also note the stalling and retreat of the northern portion of the easterly trough as the westerlies to the north pick up strength.

The development of a pressure rise building a ridge or high to the right of the northwest current behind a vigorous trough, as seems to be part of what is happening in Figure 33, has been noticed several times in transition seasons but not often very clearly in the cold time of year. In the winter the succession of strong disturbances is probably too rapid for it to show up clearly, but in a month like September, 1942, twice very clearly a ridge or upper high oriented NW-SE along the western mountains built up to the right of an extensive northwest flow over the middle United States.

Figure 34 gives the 10,000-foot maps for April 8 and 9 and suggests one of the factors which may be important in the formation of an upper high. The NW trough A seems here to be the active agent in splitting the extended ridge and feeding air into the high. Note also how the two small troughs on the southern circuit go through in a diminished state below the high. This last process is a normal one when a persistent upper high is located in a favored position in high latitudes such as near Aklavik, Northwest Territories, just west or southwest of Hudson Bay, or near Iceland and Greenland. Usually there is an indication of a ridge extending from the

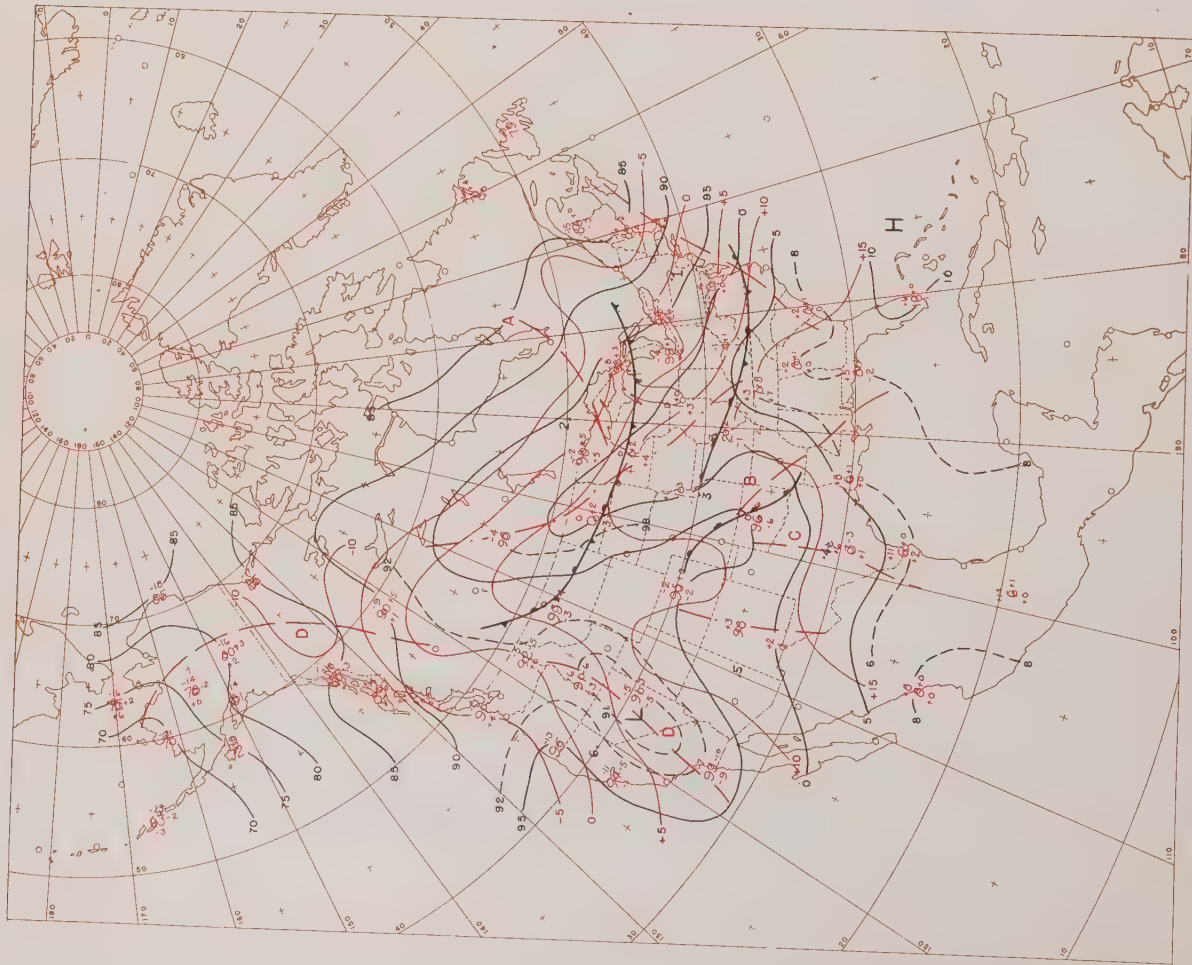


FIG. 34a.—Series showing 10,000-foot high-forming in an extended ridge. 10,000-foot map for April 8, 1943, 2300 EST.

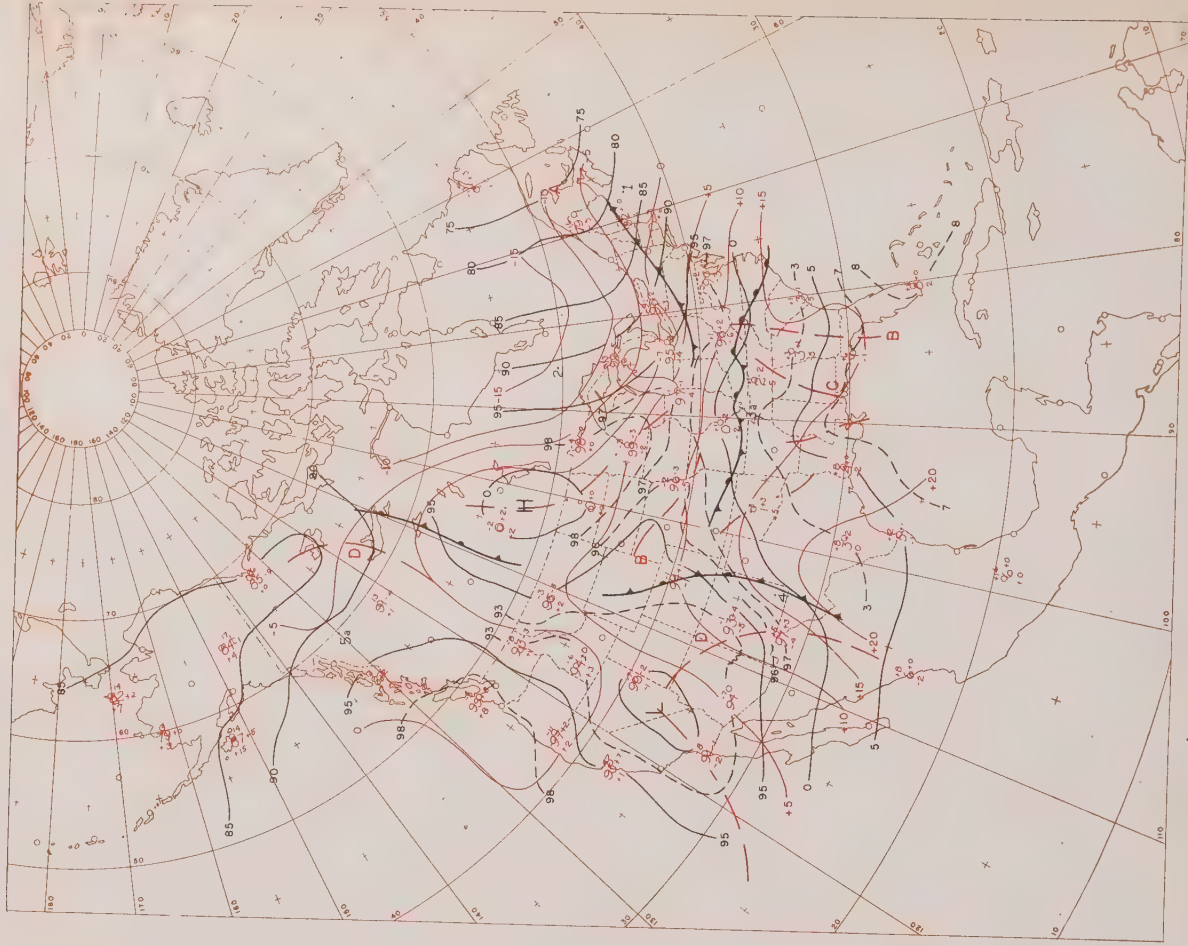


FIG. 34b.—Series showing 10,000-foot high-forming in an extended ridge. 10,000-foot map for April 9, 1943, 2300 EST.

high into the more southerly circuits, and, as troughs approach this region, they diminish in intensity, recovering on the forward side if they succeed in crossing. In situations of this kind there will frequently be closed low circulations at 10,000 feet in the more southerly latitudes. These lows either may be stalled completely by the ridge and high or may be able to make the passage, in which case the low suddenly shifts from opening into northern latitudes to the northwest or west to opening toward the northeast or east. On the northern circuit long, east-west troughs have also occurred across the Gulf of Alaska and western Canada, opening toward the west, with the northern high connecting into an extended ridge at the eastern extremity. Here, when a strong Wr trough comes through on the lower circuits with a SW pressure rise behind it, the ridge to the west can connect to the northern upper high, while the eastern ridge loses its connection and the east-west trough shifts to opening toward the east. A closed low is likely to develop and considerable deepening to occur with the Wr trough as it passes eastward. The problem in all these cases is to estimate the relative vigor of the troughs and the connecting ridge.

5. Winds

In this section we shall give some material on the behavior of certain winds derived from observing the maps and from estimating true paths, together with some indications of the utility of such winds in forecasting. A certain degree of regularity has appeared in the behavior both of currents in certain types of patterns and from certain general geographic locations, making some classification desirable.

All the names given refer to winds starting from inflection points; thus, a SW Gulf of Alaska wind is a current starting as a southwest wind at an inflection region in the Gulf of Alaska. Maximum curvature winds when discussed will be explicitly indicated and assigned to the class of winds of the first inflection point on the computed trajectory, i.e., a west wind starting from an anticyclonic curvature region would be considered with the class of NW ridge winds. A wind is considered a NW trough or a NW ridge wind depending upon a qualitative estimate of whether the ridge or the trough is the dominant influence in the vicinity of the current, but this will, of course, often be a vague or unnecessary distinction.

By way of general orientation, before going into a discussion of details, it should be stated that one of the first steps when using upper charts as a forecast tool is to locate those currents which are the strongest from the standpoints both of speed and of extent. If a map is half-covered with strong NW winds, different types of reactions should be expected than

if the strongest currents present were from the southwest. These differences, it is hoped, will be suggested in more detail to the reader by later material, but in general they are what is connoted by the terms "cold," "cyclonic," and "stormy" in the former case and by "warm," "anticyclonic," and "quiet" in the latter. Such an estimate of the predominant general current, while it may be altered by accelerations and other changes in the currents, is at least the first requisite to obtaining a reasonable forecast and will affect particularly the conclusions drawn as to what deviations of the winds from the computed paths are most likely to occur, as well as all other features of the forecast both at the surface and aloft.

a) Northwest trough and ridge winds.—For the particular case of NW inflection winds, Figure 35 gives several types of deviation from the C.A.V. path, most of which have been mentioned in section 1. Those most often found in the NW winds are such as could result from divergence, and therefore, particularly in the cold season when considerable amounts of cold, subsiding air are present, the normal expectation is a path such as A or B, or in a regime of predominating NW winds a path such as C. The path indicated by D is a convergence type and occurs occasionally when a NW trough drops in rapidly behind a wind and deepens to a closed low. E is associated with the building of an upper high to the right of the NW current and usually involves a marked deceleration of the wind as it reaches low latitudes. F and G are two alternatives which occur when a ridge builds up very strongly in the Gulf of Alaska. If conditions are favorable for the development of an upper low inland, paths such as F may occur, while if a low does not form, a parcel may move along a track such as G, or along one (not shown) that, after following F for a while, runs more or less straight toward the east.

If a strong mean ridge is located to the east, or if a southwest current stronger and more extensive than the NW one is present ahead of a trough, a NW trough wind is likely to turn approximately as required by the C.A.V. path or even more strongly. This can occur on the southern circuit even when the northern portion of the trough and current acts normally, that is, the southern portion of the trough may be stalled by such a SW current, while the NW trough wind follows the C.A.V. path, and in the north the trough continues on with divergent effects showing in the trajectories.

A type of deviation which does not seem to be connected so much with convergence and divergence as with the local rate of rotation of the streamlines (neglected in the original analysis—see p. 22), arises in certain west winds at ridge lines. Some anticyclonic winds, especially those starting from a mean ridge, work out extremely well but, some starting from rather small and briskly moving Wr ridges never do start toward the

south. The ridge in these cases moves with nearly the same speed as the wind, which in consequence follows practically a straight path toward the east. Here the curvature of the streamline at the initial point is not a good approximation to the curvature of the trajectory, as is necessary according to the theory. A somewhat similar flattening of the path, which appears to be associated with the proximity of the mountains, occurs in western Canada occasionally when a strong anticyclonic wind starts from Alaska (path H, Fig. 35). The computation may lead to a current's moving into the region of the Rockies farther south, but only low velocities will be observed there, while strong winds will occur to the northeast over the Plains.

A general idea of the manner in which the wind is moving through the troughs or ridges is a big help in deciding how these features will move and change. Though it is not true of mean troughs and ridges or certain other slowly moving types, small troughs such as H.I. or Pp-V troughs at 10,000 feet show a distinct tendency to move with the speed of the wind there. This is shown by the scatter diagram in Figure 36, which gives the 24-hour movements of trough components of all kinds in the westerlies plotted against the inflection velocity to the rear of the trough at the beginning of the 24 hours. The line A, drawn to split the group of points approximately evenly, is very close to the line where trough movement equals wind speed, in spite of the fact that even the cold types of troughs which should move much slower than the winds were included. (Some of the troughs which moved faster than the initial wind did so because of acceleration of the current during the 24 hours, but in many cases this definitely was not involved.)²¹ The spread between line A and the 45-degree line on the graph is a measure of the mean rate at which the wind passes through the trough toward the forward side and is of the order of 2° or 3° lat per day. Thus, for example, if there is a small trough which is dipping into a mean trough and for which we have no other means of estimating future movement, and the wind velocity happens to be about 35 mi/hr (12° per day), we can subtract about 2° per day and move the trough 10° , usually with fair results. There is a difference between the relation of wind to trough-speed in a mean ridge and in a mean trough for small trough components; when going over a mean ridge, the trough tends to move slightly faster than the 10,000-foot wind, while around a mean trough it tends to move slower. For small ridge components the corresponding result seems to be that the ridge will tend to

²¹The next step along this line of investigation would be to prepare similar graphs from a large number of maps considering each kind of trough separately.

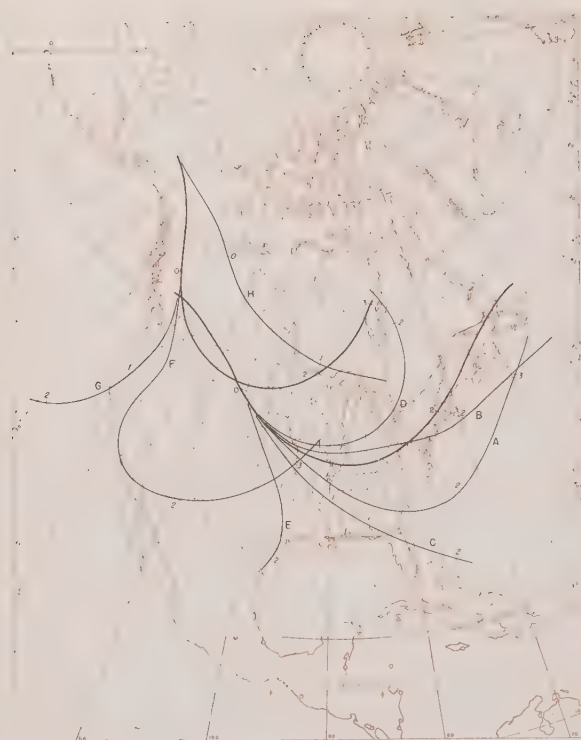


FIG. 35.—Typical paths for northwest winds. FIG. 37.—Typical paths for southwest winds.

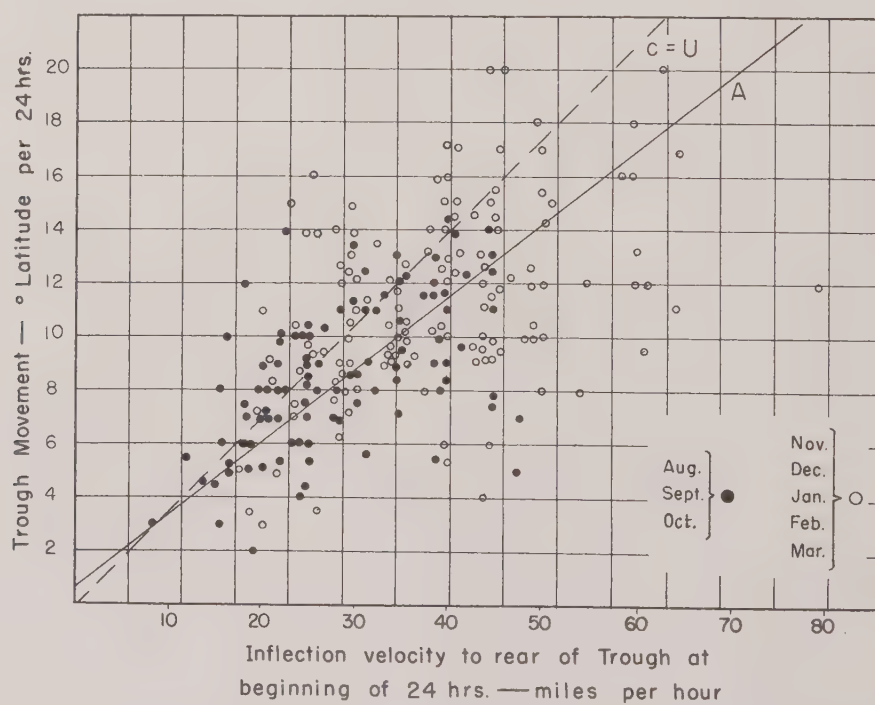


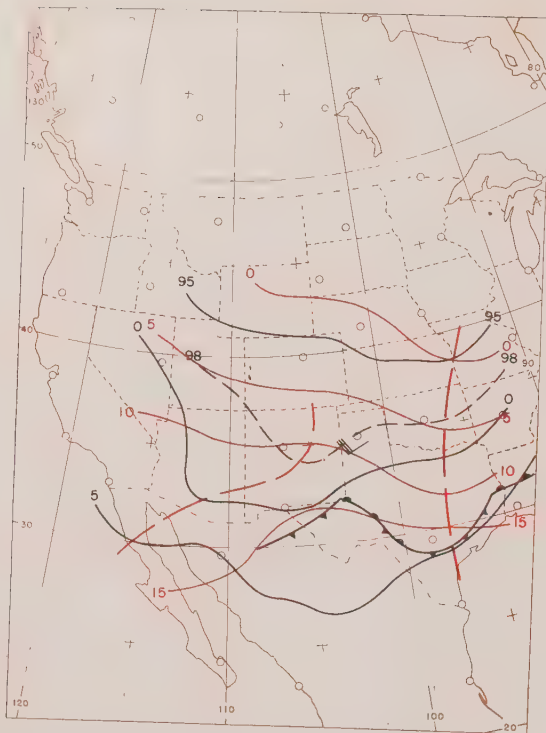
FIG. 36.—Scatter diagram of 24-hour trough movement against the inflection wind velocity behind the trough at the beginning of the period.

move slightly faster than the 10,000-foot wind when moving around a mean trough and considerably slower when going over a mean ridge (see ridge in Fig. 32, which moves faster than the wind). Account can be taken of this in a general way in the forecast by stretching forecast movements in the one case and holding them down in the other.

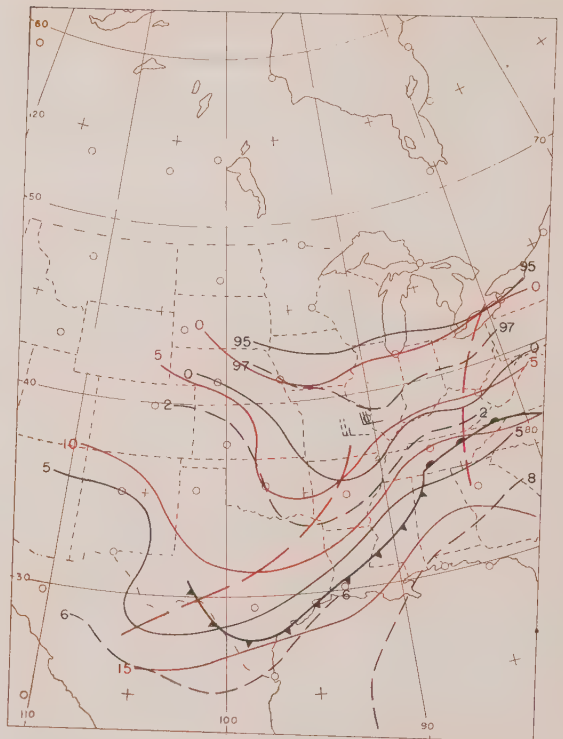
The tendency of small troughs to keep up with the wind can cause considerable difficulty in the forecast if one persists too strictly in attempting to hold the original trough behind the NW trough wind when it has become southwest on the C.A.V. path a day or so later. Even when the southwest direction does verify, if acceleration of the actual wind has taken place, the trough to the west of the wind may be the second or third one behind the original trough which moves on with the faster flow. With or without acceleration, the original trough may have become a SW trough and disappeared completely, while the southwest winds occur in front of a later Wr or NW trough.

b) Southwest ridge and trough winds.—In Figure 37 are indicated some of the typical kinds of deviation for SW inflection winds, the most common of which are such as could be due to convergence in the stream. These are A, B, and D; A occurs with NW troughs deepening to the east of a mean ridge, B with a moving extended warm ridge, and D with a vigorous, V-shaped Wr trough which moves with about the speed of the wind. C and E are the types of paths which may be associated with high index on the more northerly circuits, while F, of course, is one of those associated with the development of a strong extratropical upper low.

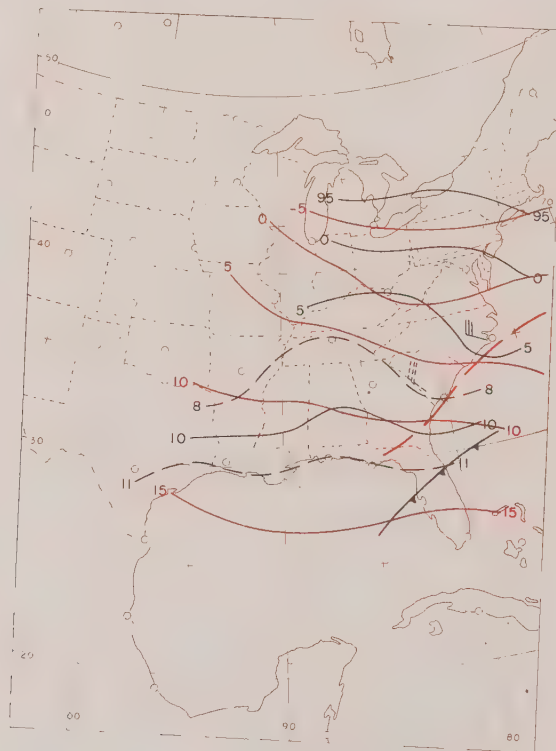
An aid in estimating the movement of a current is a consideration of whether or not the stream is a subsidiary, located to one side of a major one, since there may be more than one maximum of speed in the velocity profile across a current. This arose most frequently with SW subsidiary maximum currents of the kind shown in Figure 38. The SW trough wind ahead of a trough in New Mexico or western Texas is overtaken by the trough during the succeeding 2 or 3 days, while the wind itself follows an excellent approximation to the C.A.V. path. In this particular case the trough is not very active as it crosses the East Coast, but the same thing can occur in a trough which is quite pronounced, although the maximum intensity will be in the north. While the SW trough wind in New Mexico stands out because it so often verifies the C.A.V. path very well, subsidiary maximum currents frequently occur in northwest winds also, where the weaker southern member is more likely to head straight toward the southeast (except in cases of blocking by southwest winds on the southern circuit) and the stronger northern member



a) March 11, 1943, 2300 EST.



b) March 12, 1943, 2300 EST.



c) March 13, 1943, 2300 EST.

FIG. 38.—Trough at 10,000 feet overtaking a SW New Mexico wind.

is more often able to turn along the C.A.V. path or even more strongly.

c) Northeast ridge and trough winds.—The usual types of paths occurring with these winds have already been touched on in section 1 and generally show a divergence effect, except very close to strong upper lows. Either the wind maintains its original general direction and becomes a part of the northeast trades or it finally turns cyclonically into a straight path toward the east. As mentioned in section 1, however, there is a considerable seasonal variation in this respect. In the warmer seasons the particle may pass through at least the lower loop of the C.A.V. path, although it is probably only rarely that it then completes the northern loop, since to reach these positions requires 6 or 8 days from the starting-point (for ordinary velocities). A better approximation to the computed path than is usually found can also be expected in those slow-moving situations that sometimes occur in the cold season, when a number of small and not too strong subtropic lows and closed highs on the upper circuits are present. Here, for instance, the particle may head back north in front of the low, but this usually occurs at a location somewhat east of the corresponding section of the C.A.V. path.

There is also some probability that fairly good verification of a NE ridge wind starting from Alaska may sometimes occur when a closed low is present or develops in the eastern Gulf of Alaska. This appeared to be the case in one or two instances.

d) Southeast ridge and trough winds.—Southeast winds, especially when of recent tropical origin, are among the least likely to verify the computed wind beyond the first day. The verification on the first day will usually be fairly good, but on later days it is very likely to be poor. Convergence types of effects are the usual kind, and the parcel, instead of turning back toward the south after the first day, will head straight toward the northeast or follow an even straighter path toward a direction close to east. Even in the summertime a SE ridge wind at the western side of the one of the large upper high cells will not often turn back as computed but will keep on toward the east. In fact, the only likely situations for any considerable verification are those involving rather small, closed high cells in middle and northern latitudes. One such situation is shown in Figure 33, which shows a very approximate subsequent path for the SE inflection wind. The initial deviation to the left from the C.A.V. path (which had an anticyclonic loop with y_m equal to 13° of lat) seems to be due here to the convergence which shows up in the ending of the streamlines (lines with arrowheads) between the east and the southeast currents in the

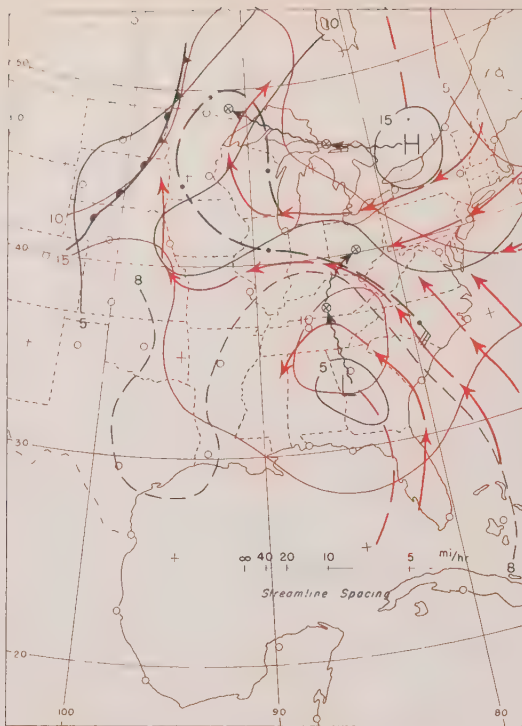
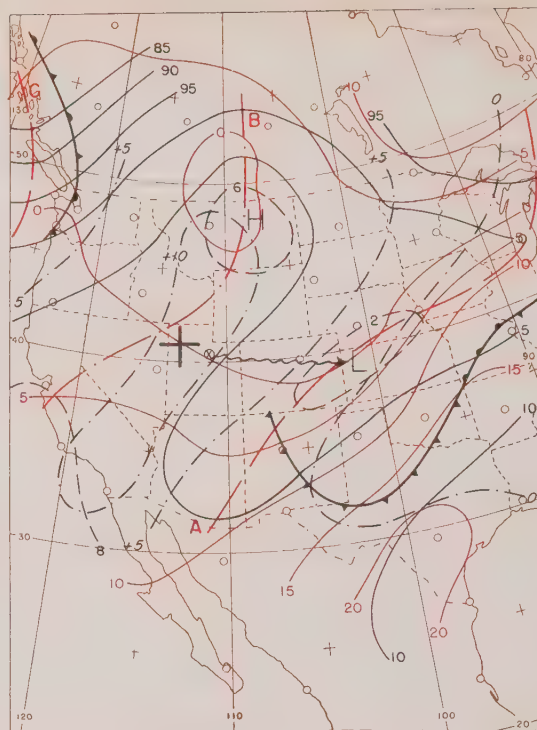
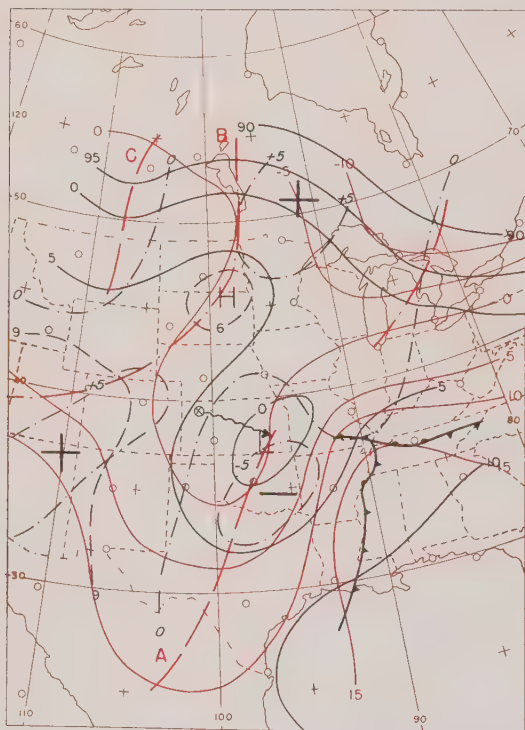


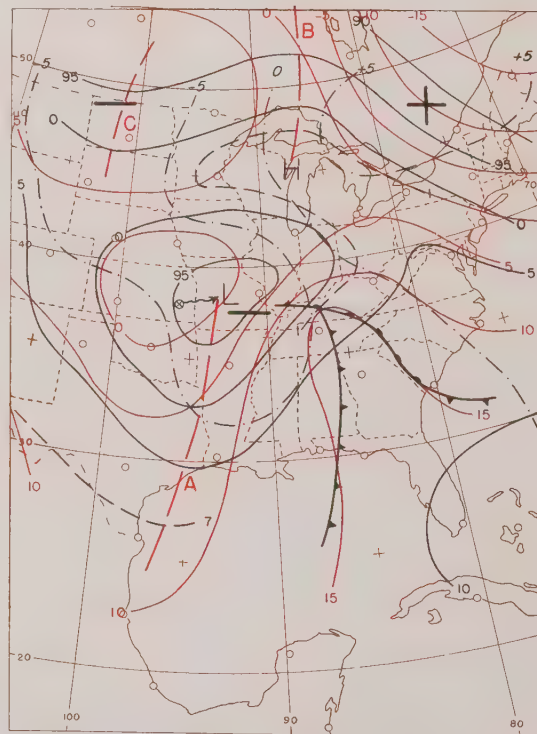
FIG. 39.—10,000-foot map for October 12, 1942, 2300 EST showing instantaneous streamlines and a SE wind path which has a loop.



a) November 20, 1942, 2300 EST.



b) November 21, 1942, 2300 EST.



c) November 22, 1942, 2300 EST.

FIG. 40.—10,000-foot maps showing a pressure-rise area moving southeastward and disappearing and also one moving across north of a 10,000-foot low.

eastern United States.²² The loop finally occurred as the closed high to the north moved westward. Most such paths do not resemble the computation even to the extent of showing the loop, but there are cases of SE ridge winds in the northern Gulf of Alaska occurring with an extensive warm ridge over the coastal regions of Alaska and Canada which approach it and which can be helpful in foreseeing the closing-off of a high in the ridge.

e) Southwest Gulf of Alaska winds.—This class of winds is on the whole probably the one which gives the best over-all verification of any on the United States map. On the first day that a strong and extensive southwest flow becomes established in the Gulf the verification is often poor, but on subsequent days, as a mean ridge persists near the West Coast, the winds go up and over it along a path closely similar to the C.A.V. path. Within 4 days the divergence effect is generally evident as the current heads toward the south. As the particle traverses this circuit, a Pp type of trough usually appears by the second day over the western part of the continent, sometimes just behind the wind and sometimes as much as 8° of lat ahead of the computed position. Whether this Pp trough will develop into a typical NW trough with attendant deepening effects and Pc outbreaks depends upon many factors, which can probably best be indicated in terms of a description of the characteristics of the mean ridge. If the ridge is located close to or just off the West Coast with a moderately accentuated form and

²²The idea of using in meteorology streamlines drawn in such a way that the number of streamlines which end or begin in a given area gives a quantitative measure of the volume transport out of or into the layer to which the streamlines apply is due to S/L C. E. Palmer of the Royal New Zealand Air Force. The streamlines are drawn so that there is constant volume transport between any two adjacent ones by making the spacing between them inversely proportional to the observed wind speed on any arbitrary distance scale such as that shown at the bottom of Fig. 39 (strictly the spacing should be measured along the orthogonal trajectories to the streamlines). When a streamline ends in an area, one unit of volume transport must be disposed of by vertical motion out of the layer (strictly again, because of the compressibility of air, the streamlines should be drawn for the specific momentum; the number which end would then give the mass transport out of the layer more accurately than the other scheme gives the volume transport [see V. Bjerknes and Collaborators, Dynamic Meteorology and Hydrography, Vol. II: Kinematics (Washington, D.C.: Smithsonian Institution, 1911)]). For an area in the shape of a rectangle, the average change over the area, in the depth of the layer to which the streamlines apply in per cent per hour is given by the formula $\frac{1}{D} \frac{dD}{dt} = \frac{14.4}{L} \frac{N}{\text{per cent/hr}}$, where D is the depth of the layer, N is the number of streamlines which end minus the number which begin within the rectangle, and L is the length of one side of the rectangle in deg of lat. The other side of the rectangle is equal in length to whatever spacing is used for a speed of 10 mi/hr. This formula will apply no matter what scale is used in drawing the streamlines.

few signs of movement inland, then conditions are best for NW troughs and cold fronts to result over the Plains. If the ridge is located inland over the mountains with a tendency for the United States and lower Canada to be flooded with warm Pp air without pronounced internal thermal gradients, then the actual path will probably be slightly flatter than the computed, the troughs will tend to be of a mild Wr type, and cold waves, if any develop, will occur mainly in the East. In this case the strongest winds over the continent will be in the northern circuit, dipping slightly perhaps into the middle circuit. Finally, if the ridge becomes a moving, extended, warm ridge or a Wester between a series of moderately active Wr troughs, then the verification will not be good, but the path will be one of those which tend not to turn back toward the south but to keep on northward for some time past the maximum point of the C.A.V. path. Occasionally a SW Gulf of Alaska wind in a series of V-shaped Wr troughs will show fair verification, but probably the actual path in these cases is considerably flatter than the computed.

f) South Gulf of Alaska and South West-Coast winds.—The class of S West Coast winds (including S winds out to about 140° W) is one which rather consistently fails to be followed by the type of low-index deepening which might be expected, with north upper winds over the continent. Instead, the current turns onto a rather flat westerly track, and over the western mountains and the Great Plains one is often confronted with anti-cyclonic conditions, closed upper highs, and a belt of westerlies displaced well above the middle circuit. This has occurred a number of times in the cold season, though there is some reason to believe that in the warmer parts of the year, with the tendency to lesser velocities, shorter spacing of systems, and more small closed upper highs, there may more often be an appreciable north current over the United States following the southerlies at the coast. The inference that such a S wind near the coast will be followed by what is essentially a H.I. condition over the continent, though the westerly velocities are usually not exceptionally strong, will break down occasionally even near the cold season, as witness the maps following April 29 (here the S current was quite weak). But even when low-index types of polar outbreaks occur, the paths are usually stretched out toward the east, i.e., the wind does not turn into north but only to northwest.

A strong S Gulf of Alaska wind from beyond 140° W longitude is more likely than winds of the previous group correctly to indicate strong northerly flow over the continent a couple of days later, but here also a convergence effect usually seems to be operating so that the actual path is spread toward the east and a strong NW current appears with its axis to the

east of the north winds on the C.A.V. path. It should not necessarily be inferred from this discussion that S winds farther out in the Pacific or in other parts of the northern hemisphere will not be followed by the development of N winds at positions to the east. The only winds on which we have any very certain data are those occurring fairly near the coast, and these behaved much as described; but it is unlikely that S winds farther out and differently situated with respect to the continent will act in precisely this fashion. As in the case of SE ridge winds, S winds starting from latitudes above 50° N have a considerable chance of coming close to the computed path, in situations in which closed highs are present or seem likely to develop in an extended ridge in the far north.

g) North Bering Sea and North Gulf of Alaska winds.—These two classes of winds are usually associated with situations having very vigorous cyclonic activity, particularly in the Gulf of Alaska. They occur most typically when a very strong ridge has built far into the north over or to the west of the Bering Sea with a strong and persistent flow of polar air directly toward the south occurring on its forward side. When the axis of this current lies mainly over Alaska and is directed toward the Gulf, the winds are classed as N Gulf winds, and events usually proceed in the following fashion. Either divergence or accelerations at 10,000 feet occurring in the deepening systems in the Gulf so modify the path that, instead of south winds over the continent later, southwest or close to west winds are observed. However, the general situation inland subsequently is not a pure type of high index. The strong occlusions coming on the coast are associated with a succession of vigorous V-shaped Wr troughs on the 10,000-foot map, and polar air swings fairly far south with each trough as it passes over the eastern part of the country. The air as it flows out over Alaska is sometimes extremely cold, and if the forecaster were merely to extrapolate the whole system, ridge and all, toward the east, he might be led to forecast a strong cold wave over most of the United States, whereas usually the N Gulf current is persistent, and instead of a tremendous cold air outburst over North America there appears a procession of vigorous occlusions coming in on approximately the middle circuit.

In contrast with the N Gulf winds, those from the Bering Sea are more likely to verify the computed south winds at the coast, although the later northern branch of the path is frequently affected in somewhat the manner of April 1-7e in Figure 14. During N Bering winds the 10,000-foot mean trough is farther out in the Gulf than in the other case, and there is more of a tendency for a mean ridge to build on the West Coast. With both N Gulf and N Bering winds of ordinary strong velocities as the wind

approaches the coast on about the second or third day we usually could anticipate a moderate to strong Pp trough coming in just about with the wind or slightly behind it; the subsequent history of this trough depends on how much of a ridge is present on the coast, general conditions over the land, and on the spacing of troughs behind.

6. 10,000-Foot Work Sheets

In the assemblages of computed winds on the work sheets it is possible to recognize certain general types of deviation from the corresponding observed winds. These will be described in this section. The differences will appear even after winds which have definitely not been verifying have been rejected from consideration and are sometimes very extensive. They have been dealt with at least implicitly in much of the preceding material, but it is helpful, especially after a little experience with the work sheets, to consider some of them in the aggregate.

Before going on to this, a word should be said about using the check sheets on the winds in connection with the work chart. It is essential to check every day the previously computed winds and to go through the work sheet and circle or otherwise indicate those which are excessively deviatory. During this process it is also possible to recognize typical deviation patterns lasting 2 or 3 days in some of the computed winds and from these to estimate corrected directions on the prognostic work chart. With experience one can more or less successfully recognize in advance those cases where a constant difference in direction between the actual and computed wind persists for a couple of days, or where the computation and actuality are merely out of phase for a while, one being northerly where the other is southerly and vice versa, or where at a constant or steadily increasing distance to the east of the computed positions the wind would have verified. (These, of course, are matters of pure empiricism.)

a) Corrections for smaller features of the pattern.—It has already been mentioned that for most trough and ridge components the factors making for deviations from the C.A.V. paths normally add up in such a way that positions of these features determined solely from the work sheet (after the rejection of winds already bad) are in error by 3° or 4° of latitude, the observed position being located to the east of the computed. Applying this correction arbitrarily to all such positions will give better results on the average than would be obtained if these positions were determined from the winds alone, but there are two or three categories for which zero or even 1° or 2° corrections toward the west are frequent. Mean troughs usually do not require any considerable correction, although care must be

taken not to hold the original trough component at the shift from northerly to southerly winds, as these are generally the cases in which it becomes a SW trough. A new component of the mean-trough complex will be located there, while the first small trough moves on toward the NE. A similar case where even westerly corrections occur is that of a strongly deepening NW trough, where, perhaps assisted by mild blocking from the high to the east, a strong and extensive SW current develops ahead, and the trough slows down for a time. With this category should also be put a few cases involving stronger blocking and not necessarily deepening of the trough, where the SW current in front of an extended trough is much more extensive and stronger than the northerly winds (mentioned in sec. 5a). The final situation in which usually little correction is needed is that of the New Mexico SW trough wind discussed in section 5b.

b) Broad aspects of the work sheet.—The cases, aside from those involving the development of strong, closed upper lows with extensive easterly currents in middle latitudes, in which broad, strong currents sometimes make an assemblage of trajectory winds look exceedingly poor, may be roughly divided into extensive SW tropic currents and strong NW outbreaks. When these strong currents develop and spread over large areas of the map, large groups of the computed winds may fail. In these cases the indicated position of the major ridge in the first case or the major trough in the second may be as much as 10° west of the observed location. The NW outbreak occurs occasionally in mid-winter after a pronounced mean trough in the East has persisted for a while. A trough finally arrives in which the air-mass differences produce such strong currents, or behind which a ridge builds and begins to move, that the NW winds break out past the coast and the trough moves past the mean trough position into the ocean as a strong W over areas where the trajectories indicate many southwesterly winds. Especially for 2- or 3-day charts the only means we have had for dealing with such cases have been to try to estimate from the pressure changes and the general situation the actions of the western ridge, or from a qualitative estimate of the temperature gradients and isotherm distribution in the trough to judge the likelihood of its producing these effects. However, there is some possibility that these developments would have been indicated by more computed winds from the Pacific, had such winds been available. In the case of the SW tropic currents it seems probable that at least part of the crucial factors will be found in the easterlies beneath and the current distribution to the east of the large upper ridge present in such situations.

In the Atlantic there have at times been enough data available to adumbrate some of the problems which will arise in working around and on the

eastern side of a major subtropical high cell. In such a region as that near the Azores the indications have been that much more north and north-easterly flow aloft occurs than is even faintly indicated in the trajectory winds, a result accordant with the considerable amount of evidence for divergence on the eastern sides of the subtropical cells. Similar deviations can also be seen at our West Coast when a SW pressure rise occurs in the Gulf of Alaska. The N and even NE winds which then develop on the coast have not been indicated in any of the trajectories available from near Alaska, and it is quite doubtful whether winds from other regions of the Pacific would indicate them directly. One case from the Atlantic provides some clue as to how the trajectories might in part be useful in this problem: in this instance N and NE winds developed even farther west than usual with a subtropic low center developing at least at the surface between Portugal and the Azores (Nov. 12-14, 1942). This was associated with a particularly consistent set of strong computed SW winds over the western part of the middle Atlantic. The implication would be that banking of the air to the right of the SW current would tend to produce pressure rises in the ridge followed by acceleration of the winds to the east into N and NE winds and formation of a low or trough structure but, of course, since the evidence rests on only one case, this is no more than a suggestion. In the case of the normal NE trade stream the problem is one of finding indications of when the trajectories are to be expected to show the normal error (i.e., verifying as N to NE and E instead of NW, W, or SW) with a normal subtropic high, and when SW or NW winds are to be correctly interpreted as implying cyclonic developments or arctic outbreaks in the lower Atlantic.

A closely related problem to that of the last paragraph is that even in the middle and western Atlantic many computed westerly winds attain latitudes almost certainly occupied on the verifying maps by easterlies. This has clearly indicated the necessity of considering the probable trajectories of easterly currents which may not be amenable to computation but which still may possibly provide some clues as to when to expect normal easterlies and when to expect the indicated westerlies in low latitudes.

7. 24-Hour Pressure Changes at 10,000 Feet

The 24-hour pressure change is a particularly valuable forecast quantity both because of the quasi-conservatism of the moving pressure-change areas and because of the index they give of the intensity and changes in intensity of troughs and ridges. As a first approximation it suffices in many situations merely to extrapolate change areas at 10,000 feet without altering their intensities, particularly for a 24-hour forecast. But much

of the time, and for longer forecasts, account must be taken of changes in intensity of the change areas and sometimes of the development of new areas or the disappearance of old ones. Such considerations are very necessary in deciding on forecast values of the 10,000-foot pressure, for even if the winds and streamline pattern are forecast perfectly, one has no more than a general idea of where the pressures are lower than normal or higher. (Once a few individual values have been determined, the wind field will, of course, be useful in drawing the remainder of the pressure field.)

One of the typical sets of changes which can occur in the pressure-change pattern is apparent from the discussion of the NW to SW trough cycle. For example, a fall of 5 mb in the NW trough may increase in area and in amount to 10 to 15 mb, then, as the trough turns into the SW current, the katallobaric area may decrease again or disappear altogether. This occurs when there is blocking from the eastern high, and, if not detected, it will usually be associated with a forecast in which the front is taken past the East Coast too rapidly and the pressures there are dropped too much both at the surface and aloft. The usual sequel is a second trough with developing pressure-fall area, which appears the next day, while the front moves past the coast and pressures fall markedly. This, of course, is just one intermediate sequence between those in which the troughs swing past the coast without hindrance and those, especially prevalent in the summer, in which the blocking is so complete that the front is stalled completely for long periods over the continent or else goes through only in the north; but it is one which can be troublesome in timing strong trough passages in the East.

Another very common sequence involves pressure-rise areas coming into the western United States. When a strong pressure rise appears at the coast accompanying the development of a strong ridge in the Gulf or just off the coast, it is rare, especially for the first couple of days after the initial development, for the pressure rise to move on undiminished into the United States. Instead, the ridge becomes a mean ridge, and the pressure rise usually drifts southeastward while diminishing in magnitude. Eventually the rise area either disappears completely, moves across the country a mere remnant of its former self, or perhaps moves into the tropics. The 10,000-foot maps for Nov. 20-22 in Figure 40 give an example of a pressure rise which disappears toward the southeast (though the case here is not precisely that mentioned above) and of a pressure rise going through to the north of an upper closed low, a case mentioned in section 3h. Note that the ridge here seems originally to have built up as a result of the strong SW winds to its west. Also of interest is the peculiar reversed distribution of the mean temperatures in the northern United States and Canada on the

22d which develops with warm westerly Pp flow into Canada in which no strong fronts are located.

Occasionally, especially after a strong development of a very large upper low in high latitudes with a slowly moving, flat mean trough on the middle and southern circuits, a pressure-rise area will develop rather unexpectedly on the 10,000-foot chart in or slightly behind the mean trough and move very slowly (perhaps even toward N or NE) while increasing in magnitude to plus 10-15 mb per 24 hours or even higher. For a while the winds remain close to west while small perturbations go through the change area, but eventually the process usually ends in the formation of an extended, moving or mean ridge with an associated increasing surface high. Sometimes this can be anticipated on the 10,000-foot map by watching the approach of a small ridge component which increases as it approaches the major ridge while a strong trough complex follows it in the west; but a number of times the most direct clue was found in the 10-km chart. The indications, while similar to those on the 10,000-foot map, were more clear cut. A pressure-rise area moving in from the west, which is extremely small on the lower chart, may be considerably stronger at 10 km a day or so before it begins increasing below. Even where the 24-hour isallobars at 10 km do not give strong indications, it may be quite evident from the isobar structure (e.g., just after a NW trough which is not followed by another has passed a given spot) that the pressure has reached a minimum value and that a ridge is going to be moving in with large rises at 10 km the next day and consequent probability of strong rises at 10,000 feet (see maps of Oct. 26 et seq.).²³

Particularly for falls with H.I. or similar types of troughs there is a definite tendency, similar to that mentioned above for rises, for katallobaric areas crossing the West Coast to diminish or even disappear altogether 2 or 3 days after appearing on the map unless some rejuvenating process definitely takes a hand. The trough may reach the coast with a pressure change of minus 5 to 10 mb per 24 hours. Extrapolating this for the first day will produce good results, but by the second day the fall diminishes to around minus 1 to 3 mb and by the third day the pressure fall may have disappeared. If the situation is such that there is deepening over the East, then, instead of disappearing, the pressure fall will begin to

²³Concerning overriding of arctic troposphere by a tropic stratosphere, see O. R. Wulf and S. J. Obloy, The Utilization of the Entire Course of Radiosonde Flights in Weather Diagnosis ("Institute of Meteorology, University of Chicago, Miscellaneous Reports," No. 10 [Chicago, 1944]) and also F. A. Aime and E. C. Johnson, Methods for the Preparation of Six-Day Forecasts (Washington, D.C.: U.S. Weather Bureau, November 1943).

increase again, having reached a minimum magnitude on the second or third day from the coast. There are all grades of cases between those where the fall disappears completely and those where cyclonic activity in the West is so vigorous that no minimum in the fall occurs.

Before passing on, it should be mentioned that particularly in the warmer seasons there are often definite limitations to the utility of displacing pressure-change areas, since these areas can be very ill-defined and general alterations in the pressure can take place simultaneously over areas the size of the United States.

8. Mean Temperatures (Sea Level to 10,000 Feet)

The mean temperature between sea level and 10,000 feet was used primarily as a means of connecting the 10,000-foot forecast with the surface forecast, but it was also important in checking isotherm-isobar relationships in the troughs and ridges,²⁴ while the 24-hour changes in the mean temperature were found extremely useful both for forecasting the mean temperature itself and as a diagnostic element for identifying important troughs and ridges by the intensity of the temperature changes associated with them. On occasion, a trough coming over a large mean ridge will be easier to locate by the mean temperature changes and the 12-hour surface pressure changes than by any other elements.

Throughout the whole year the sea-level pressure forecast made from the ordinary considerations of pressure change, extrapolation, etc., was compared with the forecast obtained from the mean temperature and 10,000-foot pressure forecasts. During the first months of the project, a number of key positions were selected on each map, and a mean temperature was forecast for each of them from which, with the 10,000-foot pressure forecast, an implied sea-level pressure was computed by means of the mean-temperature graph. If the two values were not in reasonable agreement, the whole forecast was re-examined, and one or all of the quantities adjusted until they were consistent. But this process is rather slow and thereby restricts the number of points which can be checked. An alternative procedure was therefore adopted wherein both the 10,000-foot isobars and the mean isotherms for intervals of 4 units were drawn on the prognostic upper chart in order to use the intersection method of drawing the sea-level isobars. In this way the sea-level pressures implied by the upper forecast chart could be rapidly deduced and

²⁴These relationships should strictly be checked with the 10,000-foot temperatures, but the two patterns were found to be usually closely similar.

then modified in accordance with other indications to obtain the final map.

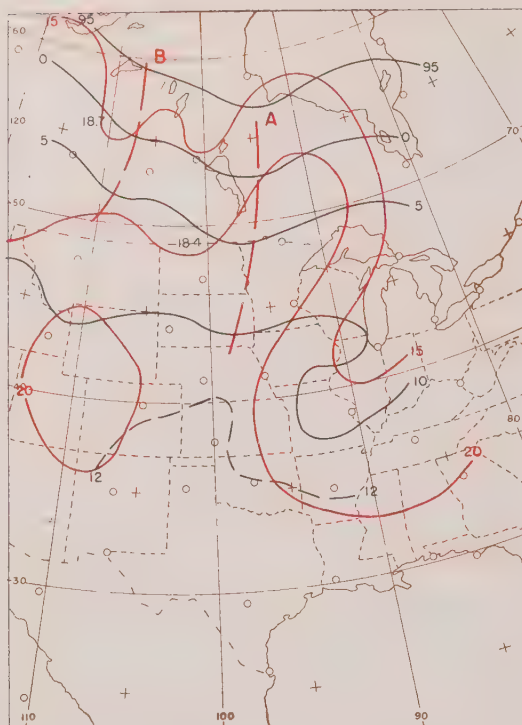
In forecasting the mean temperatures, the first step is to consider the effects of advection in accordance with the mean flow from 10,000 feet to the surface; the second is to extrapolate the 24-hour changes, modifying their intensities if necessary; and the last is to alter this preliminary prognosis on the basis of general experience with the maps and in the light of the isotherm pattern anticipated to be associated with the forecast 10,000-foot map. Advection as a matter of fact will succeed quite well especially where the isotherms are closely spaced and arranged in a large, well-defined pattern, but the instances where it must be modified are many. For example, though this particular instance does not necessarily imply a defect in the advection idea itself, if too much reliance is placed on the 10,000-foot map in estimating the flow, a mean temperature rise in the Great Plains with nearly westerly flow at 10,000 feet may be underestimated when the winds at the surface and in the lower levels are from the south and more nearly directly across the mean isotherms than the 10,000-foot winds. Similarly in the north where, partly because of the scarcity of data, a cold front coming down out of Canada may bring larger falls and lower mean temperatures than had been implied by advection. These two cases are not, however, absolutely irreconcilable with advection either in the lower levels or from regions of limited data, but there are many times when it is impossible to account for the temperature change solely by horizontal advection. For instance, on May 21 and 22 at the West Coast, north and northwest winds occurred on the eastern side of a ridge at all levels to 10,000 feet, cutting across east-west mean isotherms in the California region, yet the mean temperature did not fall at all and actually rose on the 23d. This would seem to have been caused to some extent by radiative heating but probably was mainly the result of divergence and sinking with consequent dynamic heating of the whole mass of air in the lower levels on the eastern side of the ridge. A similar dynamic effect, involving convergence and lifting, we believe we have observed in certain subtropical upper closed lows which develop or maintain a mean temperature minimum that is difficult to account for by advection (see Fig. 39).

The Rocky Mountains exert an effect on the mean temperatures which very often disturbs an advective estimate to some extent. When a Pp trough with a pronounced warm tongue is coming across the mountains, it is quite common in the warmer seasons for a closed maximum of the mean temperature (25° C or more) to develop in the warm tongue on the lee slopes of the mountains. These temperatures may be higher than any observed in the warm tongue at the coast or as it crosses the mountains, or, in fact, higher than

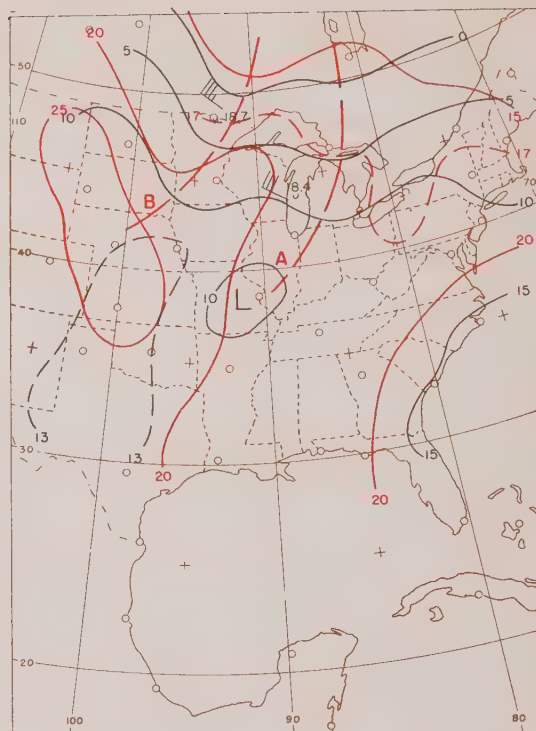
any temperatures anywhere else on the United States map. As the trough moves east over the Plains, the closed isotherm disappears and the temperatures drop a few degrees to more normal values. Even where such a closed center does not develop, it is common in such warm tongues, when there is not too much cold Polar air over the northern Plains, to see a maximum northward displacement of any given isotherm in the warm tongue as the tongue crosses the area to the lee of the mountains followed by a retreat southward again over the Middle West. At the East Coast in the winter, especially when a Hatteras Secondary or similar storm develops, it is again frequently the case that high mean temperatures will appear in the warm tongue well north of where they have been over the continent. A single warm tongue then can reach one maximum extension at the Rockies followed by another off the East Coast as a strong storm develops.

Certain deviations from simple displacement of the isotherm pattern regularly show up which are in some ways analogous to the internal changes of troughs and ridges. There are situations, mainly in the warm season, when a mean warm tongue will persist at a given longitude for considerable periods, while small warm surges with minor troughs either disappear into it or, less often, pass on through and out toward the east. These minor warm tongues often disappear also as they proceed in a field of NW winds with general NW-SE mean isotherms or when approaching a slowly moving mean cold tongue. Figure 41 is an extreme example of the extent to which not too vigorous warm tongues can change and disappear in the latter case. Finally, even when the large pattern is moving, a number of transformations can occur, such as two warm tongues amalgamating into one large one, or one of a pair of warm tongues disappearing when two vigorous troughs try to deepen so close to each other that the cold advection behind one counterbalances the warm advection ahead of the other or vice versa.

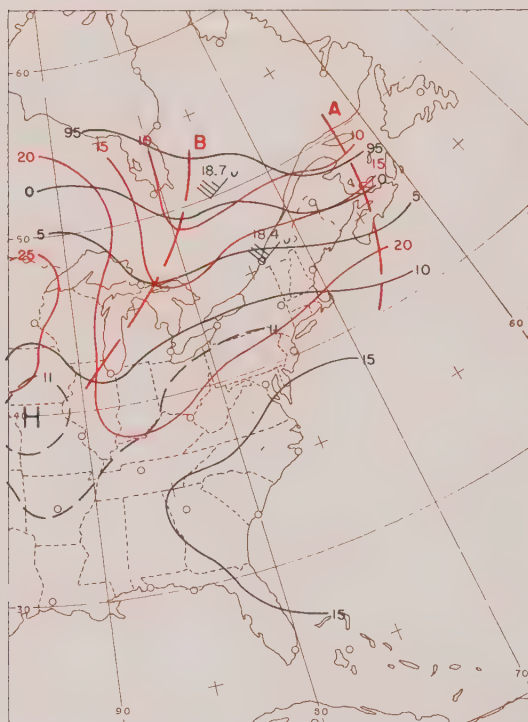
The gradient of the mean temperature is a measure of the potential energy of air-mass position, which is generally accepted as an important source of kinetic energy in the storms of the westerlies, and can with a little caution yield some useful general forecasting indications. The stronger the packing of the mean isotherms to the rear of or in a trough, the likelier is a strong, cold-air outburst or a deepening, vigorous storm. The dividing-line between gradients which may be described as moderate or strong and those to be considered as rather weak is roughly around 15° C per 10° of latitude; when the thermal gradient reaches 25° or 30° per 10° of latitude, vigorous types of developments should be expected in general on the map. However, there are some anomalous occurrences in this connection which will probably not be explained satisfactorily until a complete theory



a) August 18, 1942, 2300 EST.



b) August 19, 1942, 2300 EST.



c) August 20, 1942, 2300 EST.

FIG. 41.—Changes in small warm tongues on approaching an extensive cold tongue of the mean temperature.

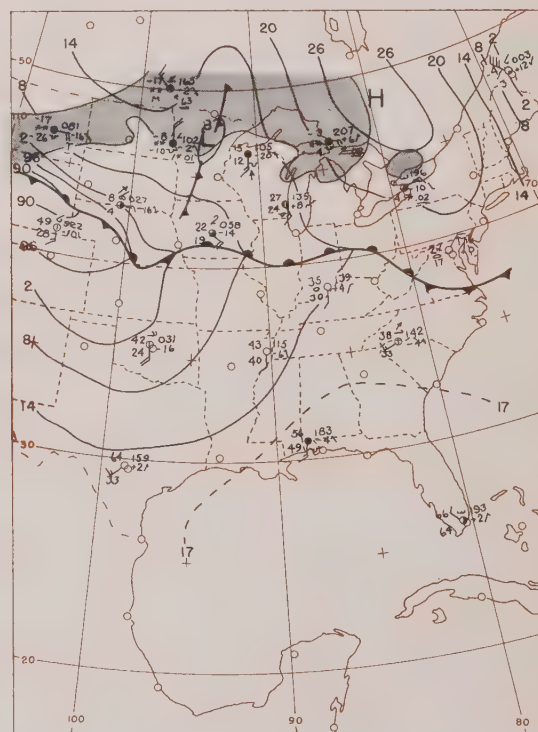


FIG. 42.—Surface map for January 22, 1943, 0130 EST in the middle of a series showing development of a cold front behind and below a slowly moving surface high and ridge.

of the energy processes in cyclones is developed. A strong temperature gradient may exist without the development of a deep low, or such development may be delayed for several days as happened on January 15-17, 1942. Here very strong mean temperature gradients were present over the eastern United States with an arctic front, but the 10,000-foot chart showed the development of southwesterlies parallel to the isotherms, and the surface low did not become particularly strong or deep until the 17th, when it moved out past the East Coast with strong NW and W winds at 10,000 feet behind it.²⁵ In other cases the mean temperature gradient becomes strongest after deepening has already been nearly completed at the surface. This occurred with a very deep storm in the East at the end of November, 1942: the main deepening at the surface from 1002 to 975 mb took place between Nov. 30 and Dec. 1, while the main 10,000-foot deepening from 662 to below 650 mb occurred between the 1st and the 2d. The temperature gradients within the main trough were 20° C per 10° latitude on the 30th and 25° to 30° C per 10° latitude on the 1st. The use of other principles would be necessary in forecasting this extreme deepening, since the initial gradient of 20° C per 10° latitude is quite ordinary for situations not showing such vigorous changes.

9. Characteristics of Large-Scale Patterns

The consideration of types of occurrences which develop over several days or weeks is very helpful in the daily prognoses and in a few instances may be crucial for as short a forecast as 24 hours. Identifying such sequences is easiest on maps such as 5-day mean-pressure charts,²⁶ but, particularly for those spread over a period of not much more than one week, a proper inspection of the daily maps can reveal in a general way what is going on once one has some idea of what to look for. The first subsection below describes briefly some of the features which are especially stable and a few of the longer-period changes which go on in them.

a) General changes in patterns.—As has been mentioned before, large mean or extended ridges on the 10,000-foot chart often condition the characteristics of the map for considerable periods. Favored locations of these are over the western mountains, off the West Coast, occasionally over or west of the Bering Sea, and near the East Coast. Northern closed highs are frequent over Alaska and the Aklavik region, near Hudson Bay, and around Greenland and Iceland (see p. 77). Ridges in the western locations especially

²⁵For further reference to this period see p. 100.

²⁶J. Namias, op. cit.

are likely to be of the mean type and quite stationary or slow-moving. This consideration alone is a great aid most of the time, but there are also recognizable processes whose onset indicates when the pattern is going to move or change radically in over-all appearance.

Anticipating the beginnings of movement of the ridge eastward is a difficult matter for which the relative intensity of trough activity to the west, the amount of extension southward of the pressure falls, and the blocking action of currents to the east must be considered (see sec. 4). Movement westward or disintegration of the mean ridge, however, usually involves a fairly clear-cut process of retrogression of a mean trough located to the east by means of a succession of NW troughs which extend their influence farther and farther westward. The more rapidly these NW troughs follow each other in swinging down toward the mean trough, the more tendency there is for pressure falls to develop or to maintain themselves and the less for the ridge to move or develop eastward with attendant rises. Usually this retrogression process does not take the axis of the NW currents much beyond the main range of the Rockies with the ridge line near the coast, but if a new strong ridge develops with SW pressure rises in the western Gulf of Alaska or even farther out, then the retrogression of the mean trough can continue out past the coast.²⁷ A strong NW trough then approaches the old ridge which either disappears completely or moves off eastward much diminished for a while (this ridge component can intensify again farther on). Occasionally the NW trough which displaces the old ridge is highly accentuated, with north winds behind and close to west winds in front, and in these cases the trough seems to move very slowly for a while (see Fig. 27). From our data it was not possible to ascertain whether the trough was being replaced daily at nearly the same position by a new, intensifying trough in the north current, whether it was precisely the same trough moving very much more slowly than the wind, or whether it was an induced structure due to a northern upper high in the western ridge while regular Pp troughs continued coming through on the middle and southern circuits in the westerly circulation. Though the first alternative is very common in other circumstances, it is probable that the latter two are more applicable to the present case.

In the East one of the major longer-period ridge problems is that of foreseeing the intensification of a ridge moving in or of a weak one already present near the coast into a strong, mean feature or slowly moving extended

²⁷The most well-defined example of this in the series occurred in the middle of January, 1943, when the strong N to NW winds and pressure rises near the Bering Sea in the western ridge gave a couple of days' warning of how far retrogression would go.

ridge. This is often connected with the transformation of Pc cold highs to warm dynamic ridges or centers,²⁸ but we shall mention here only two points which are not necessarily connected with this process. First, occasionally a strong cyclonic wind starting from the bottom of a large active trough to the west will give an indication of the increase in intensity of the ridge by contributing to a predominance of southwest currents ahead of the trough on the work sheet; this direct indication will usually only be present for a 1- or possibly 2-day forecast. Second, at times during the warmer seasons when a weak anticyclonic circulation is located over the eastern part of the country, pressure rises and an intensification of the ridge at the coast with increasing southwest currents on its western side have seemed at least to coincide with the arrival of a pronounced easterly trough past Florida. The whole process gives the impression of being related to the pressure rises behind the easterly trough.

For troughs and lows, trends over several days in the behavior of such features as the Icelandic and Aleutian upper lows, 10,000-foot mean troughs in the East, and the upper lows which progress up into the region of Davis Strait are well known. They are either connected with the classical frontal theory of the occlusion and decay of lows or have been implied in previous material and consequently will not be taken up here.

b) Spacing of troughs and ridges.—As has become evident from various parts of the preceding text, an important segment of our forecast thinking came to depend upon a consideration of the distance between troughs and ridges in conjunction with their intensities judged on the basis of the amount of accentuation of the patterns, the strength of the winds, and the general level of pressure in them, with the pressure and mean temperature changes as auxiliary indicators. The ideas used in a general way, subject, of course, to modification on the basis of other indications, were the following. If two strong troughs are separated by a considerable distance, whose lower limit seems usually to be around 17° to 18° of latitude, then especially if the western system is deepening, there is a tendency for the ridge between to intensify and the pressures in it to rise followed by accentuation of the trough to the east and deepening in it. The net effect of the process is to produce a lower-index type of situation with usually slowing of the rate of movement of storms. However, if the spacing is closer than 17° and the ridge between holds up as the western storm deepens, then the effect is to accelerate

²⁸H. Wexler, Some Aspects of Dynamic Anticyclogenesis ("Institute of Meteorology, University of Chicago, Miscellaneous Reports," No. 8 [Chicago, January, 1943]), and see following subsection.

the eastern trough rapidly until the spacing has increased beyond 17° or 18° of latitude.

Usually, however, when the spacing is less than 17° , the ridge between the two troughs is not very pronounced, and, instead of the ridge's increasing in intensity and moving rapidly for a time, other developments take place which depend mostly on the relative intensity of the troughs. If these intensities are about equal and both troughs possess potentialities of deepening, the proximity of the two will offset this tendency until one or the other has gained the upper hand. If the western one becomes the stronger, the other weakens and is either boosted up and perhaps over the ridge ahead with the characteristics of a SW trough or disappears entirely while still in the general zone of influence of the larger western system. On the other hand, if the eastern trough becomes the major one, the western one weakens and either disappears or remains a minor member of the whole complex which moves on east with comparatively little change in the relative positions of the two troughs.

These propositions were used mainly with fairly vigorous and large-scale developments (in fact, often minor troughs should be left out in evaluating the type of spacing of the important features), but analogous ideas, involving, of course, different limiting values and not such drastic changes, were helpful on a smaller scale with features of only slight or moderate intensity.

10. The Surface Chart

It will no doubt seem to some that in the preceding material insufficient attention has been devoted to the surface chart. This is a just criticism, but it has been necessary to follow this course for the following reasons: first, it would be impossible to compress an adequate description within remotely reasonable limits of space even were we aware of all the important relations between the surface and the other charts or of all the useful clues on the surface chart alone, and, second, since the surface chart is the most familiar of forecast tools, almost all of what could be said would be merely a rehash of material available elsewhere. On these grounds only enough additional description will be given in this section (a) to indicate some of the types of correlation which can be made among the various charts, (b) to suggest some of the surface forecasting principles which seemed important, and (c) to draw attention to one or two of the occurrences which have not yet been clearly described either theoretically or practically. The proportionate amount of space here devoted to this subject is much less than would be warranted by the extent to which we were able to use the

surface chart in the forecasts.

a) Surface fronts and waves.—There are a number of fairly consistent relations between upper charts, in particular the 10,000-foot chart, and the surface fronts, which further extend the uses that can be made of the 10,000-foot prognostic chart and the checks available between the surface and 10,000-foot forecasts. The normal displacement of a front such as a Pp occlusion from its associated 10,000-foot trough is 1° to 3° of latitude, so that a first fix on a surface frontal position is 2° or 3° ahead of the forecast trough position. In deepening situations as Pc air becomes involved in the eastern United States, this displacement tends to become greater, particularly between the front and the major trough, since the original frontal trough at 10,000 feet often becomes a SWr under such conditions. On the other side there are occasional cases of a 10,000-foot trough directly over the surface front (Apr. 22), and especially near the subtropics on the southern portions of the map it is common for the 10,000-foot trough to move out ahead of the surface front. Just what happens to troughs and currents at the intermediate and higher levels in these and in the extratropical cases of deepening, where as many as two trough components at 10,000 feet may pass the surface front, is a question which deserves a full three-dimensional investigation.

When the surface front is lying more or less parallel to the upper flow, small stable or developing waves on the front are usually associated with small 10,000-foot troughs lying across the front and a degree or so behind the crest of the wave. Whether the wave will develop can then be to some extent determined from the amount of accentuation of the trough. The amount of extension of the cold front southward can be judged approximately from the present or probable future amount of north-south flow on the upper chart behind the trough. (This is one instance of the application of the general steering principle that the upper flow tends to indicate the direction of movement of surface systems.)

A specific instance of the application of steering ideas occurs with the cold-wave problem over the middle United States. One should be extremely cautious of forecasting a strong Pc cold front to come down rapidly over the central Plains when a strong surface low is already approaching the Washington-British Columbia coast and the upper flow inland consists of strong and relatively flat westerlies. Only when something approaching a V-shaped trough has come in and the upper winds shift to northerly is the front likely to start moving rapidly south, though before this it can press gradually southward across the border states. Such steering considerations are very useful, but one must be on guard against occasional glaring exceptions. For instance, between March 5 and 6, 1943, a "Norther" with strong cross-

isobar flow in the lower levels traveled from 31° N to near Vera Cruz around 19° N in 30 hours, while the 10,000-foot flow over the northwestern Gulf of Mexico and the surrounding coasts remained continuously from close to due west at a force of 6 to 8 Beaufort. This same problem also arises with cold fronts over the central United States just east of the mountains, where, when a fairly strong cold air mass is involved and if the beginning of the break-through can already be detected, it is usually safest to forecast the front to swing rapidly all the way to the Gulf, even though the 10,000-foot flow does not show particularly strong northerly components.

The wave problem, both with the classical frontal waves and with the pressure oscillations within Pp currents, where sometimes fronts are not very evident, is one for which the surface pressure changes (both 12- and 3-hourly) are pre-eminently useful. These uses have been extensively described²⁹ so that we shall point out here only the considerable utility of pressure rises of a Pp type on the 12-hour chart. A large and extensive Pp rise behind a wave or low is often one of the first indications that the disturbance is the final member of a family or that it will be strong, whereas previous members of the series had been relatively weak. Furthermore, though vigorous pressure falls ahead of a low do not necessarily mean rapid movement, when they are associated with an extensive 12-hour rise to the rear, rapid movement almost invariably follows. Finally, with reference to a somewhat different problem, the build-up of a strong continental high in northwest Canada, which is one of the prerequisites for a really vigorous cold wave in the United States, seems sometimes to come with the arrival of a SW Pp pressure rise from the Pacific.

b) Surface highs and lows.—To illustrate some elementary ways of thinking about a forecast, let us consider some of the possible histories of highs coming into the United States behind a cold front and correlate this as much as possible with events at 10,000 feet. When such a high moves down, the most common direction of movement is toward the southeast or east, the high itself either maintaining its identity or amalgamating with an extension of the Azores High somewhere near the coast. In the first case it will usually be associated with an extended, moving ridge at 10,000 feet; and when this ridge is increasing in intensity, often the surface high will slow up and stagnate as a strong, warm center near or on the coast and

²⁹A. J. Henry et al., Weather Forecasting in the United States (Washington, D.C.: Government Printing Office, 1916); various U.S. Weather Bureau mimeographed notes and Professional Notes; S. Petterssen, "Kinematical and Dynamical Properties of the Field of Pressure with Applications to Weather Forecasting," Geof. Publik., Vol. X (Oslo, 1933).

will exert a blocking action on further troughs from the west. In the second case, in which the high finally loses its identity as a center, the ridge at 10,000 feet will tend to be minor and, in fact, conditions there may be predominantly cyclonic. When there is a strong Basin High located in a fairly northerly position while vigorous NW 10,000-foot troughs are coming down over the Plains, the surface highs behind the successive fronts first move SE or SSE into the middle or southern circuits and then fade westward into the Basin High as the warm tongue of the succeeding trough overtakes them, while at most weak surface ridges in the isobars move on east behind the fronts. Finally, especially after a strong low has deepened and stagnated somewhere over the northeastern part of the continent and a very strong and extensive NW and W polar flow has been established at 10,000 feet, the high behind the front can string out into a long surface ridge stretching from the northern plains toward the southeast and east. This long, narrow high remains fairly stationary until the situation is changed by the next strong disturbance (such a flow is likely to damp out many of the smaller perturbations which come into it from the west) and, depending on the general situation, then can finally break up into a number of small centers, swing bodily into the subtropical high-pressure belt, or become a large, warm center.

For surface lows, two points appeared particularly noteworthy. First, several times a small secondary low formed at the peak of the warm sector of a strong occluded cyclone having a 10,000-foot low center, while the other center remained back along the occlusion. This process has been described early in the development of frontal theory (Skagerrak Secondary) but has not been very prominent in accounts of United States meteorology, though it occurs on occasion in cases not involving the well-known Hatteras type of secondary. If the possibility of the development of a secondary is not considered, the indications of movement for the secondary may be erroneously applied to the original low, which is then forecast to move too fast with consequent ill-effects on the timing of weather. Second, the influence of a Hudson Bay High in the spring on approaching lows can produce very profound deviations from what might be expected from extrapolation procedures applied to a given low. It is an old rule—and a good one—that when a Hudson Bay High is building in spring above the Great Lakes, surface lows are unable to move on eastward below. The low center can disappear completely on the western plains, where normally it should be developing, and, in fact, warm-front rain which has already started in the Middle West can retreat and disappear without ever having reached Chicago and points east.

c) Orographic effects and miscellaneous topics.—In forecasting the pressures, there are a number of orographic effects which must be considered, if only qualitatively. At the surface the trough in the lee of the Rockies during westerly flow where frequently small, evanescent centers appear, and the ridge which bulges down the coastal plain of the Appalachians when a high is located in the north, and at 10,000 feet the slight trough just east of the Rockies in high index are familiar examples. Once or twice with strong northwest flow aloft, a surface ridge to windward of the Appalachians has seemed to be the counterpart of the lee trough. Both at the surface and aloft it is common in many types of situations for a trough to be located along the Imperial and Sacramento valleys of California. Even in high index there is often a small trough at 10,000 feet running down the Imperial Valley which usually is relatively stationary and, at least from the large maps, does not seem to have any pronounced weather effects.

Often in the course of making a set of prognostic charts, one is distinctly dissatisfied with the results which, say, develop on normal models from the previous maps, without being able to decide on possible alternatives. A first step toward improving the forecasts, then, would be to survey the possible developments which differ from the usual practical or theoretical descriptions; this would be followed by an attempt to correlate these possible developments with previous conditions, which might serve to indicate when they are to be expected. Figure 42 gives the surface map over the Middle West for January 22, 1943, during one such type of situation. The small low and cold front in the surface trough just west of Duluth, Minnesota, developed in situ during the previous day after the high northeast of the Lakes had come down behind a secondary cold front and more or less stalled to the right of strong northwesterly currents at the surface and aloft, behind a strong low somewhere to the northeast near Davis Strait. During this and the succeeding day the front was first stationary, then began to move slowly eastward, while in the strong westerly winds above it at 10,000 feet several small troughs went through producing extensive changes in the precipitation pattern. Then by the midnight map of the 22d a moderately strong trough at 10,000 feet arrived behind the surface front and low with considerable mean temperature rises ahead of it, and the surface front began to move rapidly eastward producing definite frontal effects as it crossed the area; this front arrived at the East coast by midnight of the 23d. The Canadian high meanwhile slipped southward across New England and disappeared completely as the weak surface low with the front crossed its former position and vanished into the persistent cyclonic circulation in the northeast.

Another such peculiar situation occurs when there is a mean 10,000-foot trough over the western United States with a large ridge out in the Gulf of Alaska. A persistent low-pressure condition at the surface will prevail over or near the Basin, while to all appearances there is nothing but one large Pacific high out in the Gulf; and yet, at intervals, a moderately deep low will develop and acquire marked fronts over the mountains and then move on eastward as an important system. From our data it was extremely difficult to trace any fronts coming in from the Pacific to set off these lows, though that might be the normal expectation. With better coverage it may be possible to trace surface systems coming in either from the north or from the south and southwest below the oceanic high in some of these cases, but it is doubtful if anything well defined can be found except on the upper charts with many of them. Our feeling is that troughs on the 10,000-foot map will probably give definite indications of when to expect these lows and fronts to develop.

As one final miscellaneous example let us consider the 10,000-foot map in Figure 43 which illustrates another one of the ways in which the upper forecast can be useful for deducing the surface weather and which, incidentally, suggests a technique possessing interesting possibilities for development. The figure gives three successive positions of a trough line and the winds and streamlines relative to the trough on Sept. 14, the middle day of the period.³⁰ The data were obtained by taking a value of 21 mi/hr from the west for the velocity of the trough at the time of the Sept. 14 map and subtracting this vectorially from the pilot-balloon winds. This gives the velocity of particles with respect to the trough and, since it amounts to subtraction of a field of uniform translation, does not change the values of convergence or vorticity in the field. The stippled area along the zone of convergence of the streamlines defines an area of cloudiness and thunderstorms surrounded on all sides by clear conditions and located several hundred miles from the nearest definite surface fronts. This patch of weather marks the meeting-place of two fairly well-defined currents on the ordinary 10,000-foot wind map—in this case one from a westerly quarter and one from a southerly—but a similar occurrence is possible for currents in other orientations, in particular one westerly and one northerly. Now, of course, the convergence

³⁰ Note that the streamlines here are spaced very roughly and are not related to the speed of the wind. The only condition they satisfy is that at every point the streamline is parallel to the velocity vector and consequently the lines can meet or angle into one another, occurrences which for the constant transport streamlines would imply infinite velocities.

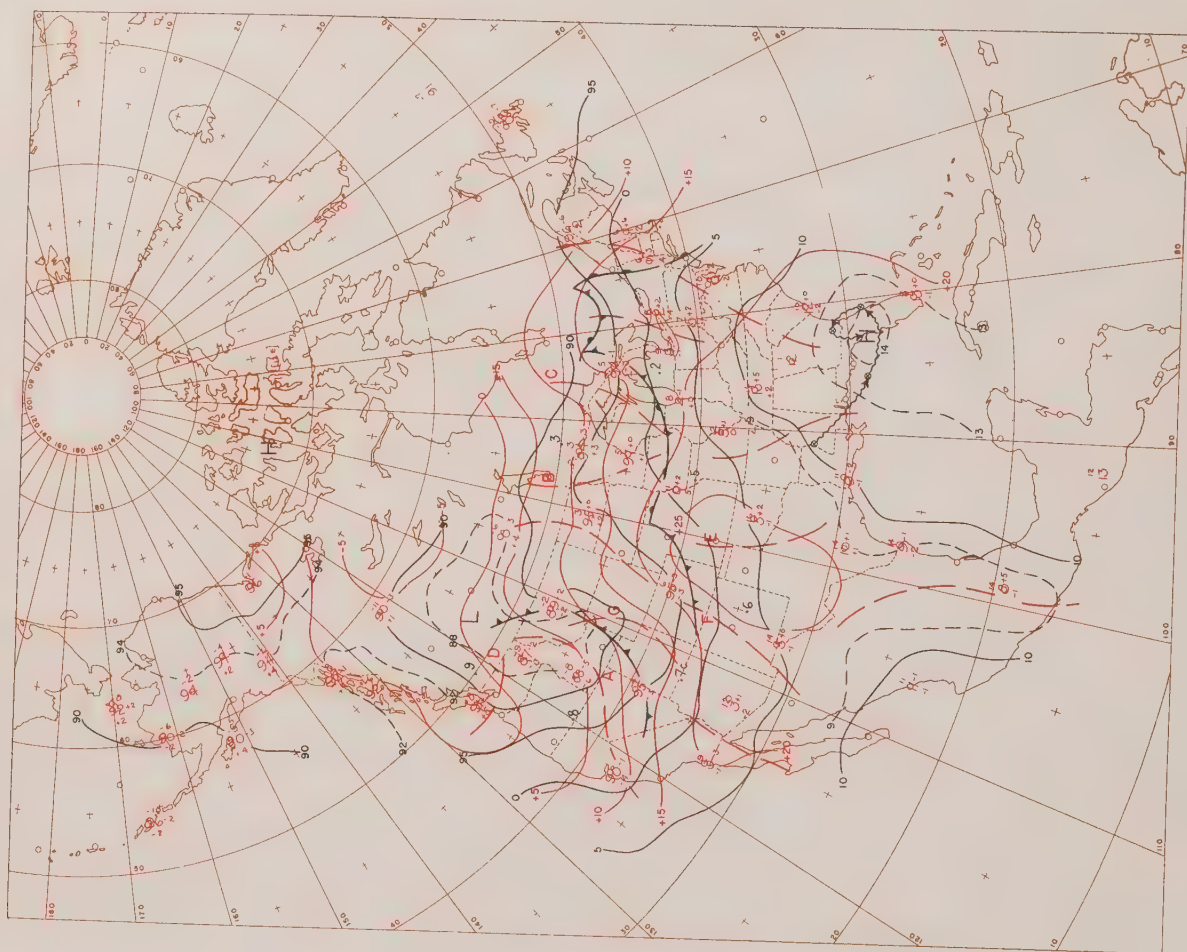


FIG. 44a. —Forecast Example: Observed 10,000-foot map for June 1, 1943, 2300 EST.

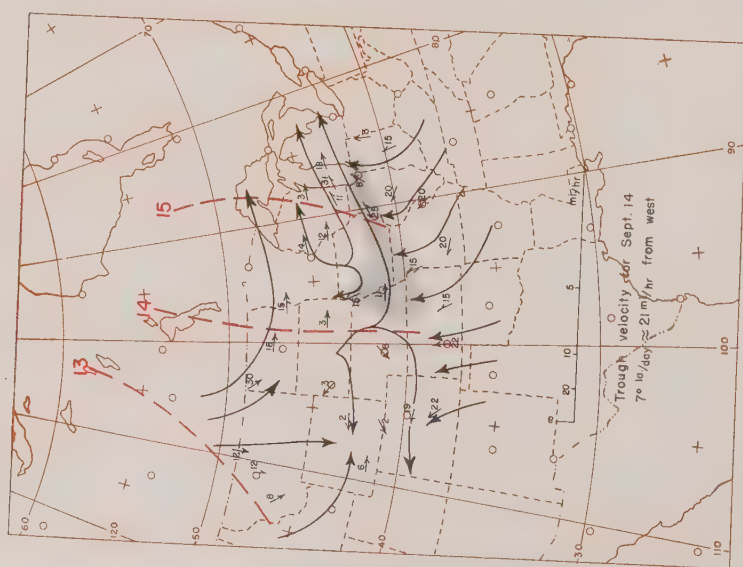


FIG. 43. —10,000-foot streamlines relative to a trough on September 14, 1942, 2300 EST.

shown on this 10,000-foot map does not determine ascending motion, since that depends upon the integral of the horizontal divergence from the ground up; indeed, such a junction of currents on the 10,000-foot chart can be associated with descending motion and clear weather under the proper circumstances. But this example does suggest, first, that the 10,000-foot prognostic chart, particularly the forecast wind field, if sufficiently good, can be directly useful in determining the forecast of weather, and, second, that the scheme of drawing streamlines from the actual data with respect to the moving systems by subtracting either a uniform translation or perhaps a uniform rotation if a trough line is swinging around the arc of a circle, has possibilities of suggesting pictorially details of structure which might otherwise be overlooked.

CHAPTER IV

GENERAL CONCLUSIONS

1. Example of a Forecast

In order to describe the detailed procedure of formulating a forecast, it was thought desirable to give an example of the 24-, 48-, and 72-hour prognoses. As it turned out, however, there was available from the year no series of charts complete in all details of mean temperature and pressure forecasts for all 3 days. Therefore, toward the end of the year, 2 days were taken for a preparatory period, and on the third day we drew up the series for June 2, 3, and 4, 1943, which is here given, the decision having been made beforehand to use it no matter what the result might be. The lessons which it contains are well illustrated by the observed and prognostic maps of June 1, 2, and 4 that are presented in Figures 44, 45, and 46.

The mechanical details having been completed, the first step in making the 10,000-foot forecast was to go through the computed winds on the working bases and from the check sheets determine and mark with a circle those winds that were already completely off and to estimate corrections for any on which an estimate seemed possible. On the work sheet for June 2 (Fig. 45a), 28-2a was rejected, since previous checks were both poor and showed no consistency, 26-7 and 28-7 had out-of-phase checks for 3 previous days and were therefore changed as shown, while 31-8 verified SW instead of WSW on the 1st under circumstances tending to indicate that a constant correction to the left was to be expected.

After the checking of the winds, the general outline of the forecast solution must be roughed out. From an over-all inspection of the assemblage of winds to see where principal troughs and ridges are indicated, and from all other available material, a tentative general solution should be arrived at. This will then determine in large measure the later detailed decisions, while they in turn will react on the general conception and modify it in greater or less degree. In the forecast before us for June 2 the fundamental features are: recognizing the major importance of trough A and the build-up which should be expected of the ridge approaching the Lakes. On the 1st, trough A was associated with the maximum velocity currents of force 6-7 in the western United States (in the Medford-Boise-Ely region); the 10,000-foot pressure fall in it, while not excessive, is moderate for the season; there

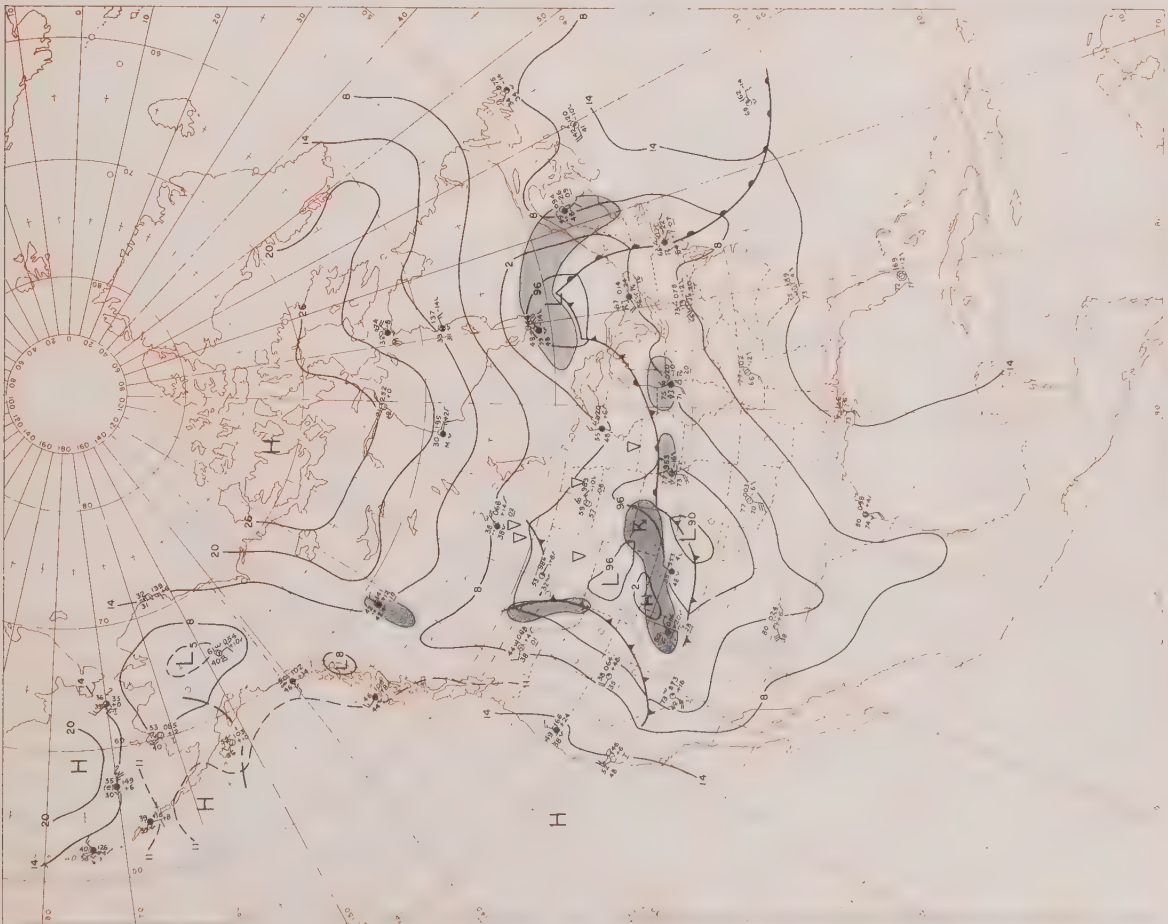


FIG. 44b.—Forecast Example: Observed surface map for June 2, 1943, 0130 EST.

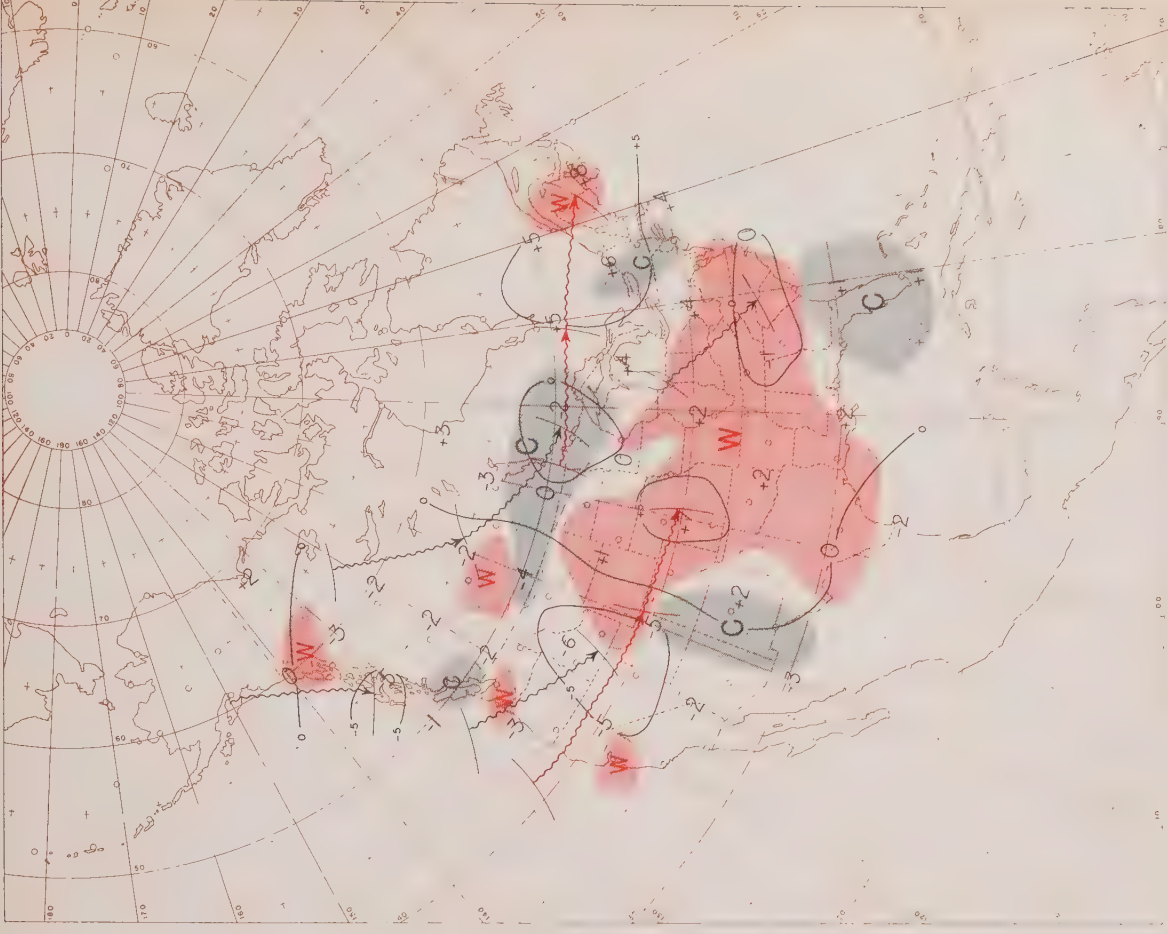


FIG. 44c.—Forecast Example: Observed advection map for June 1, 1943, 2300 EST.

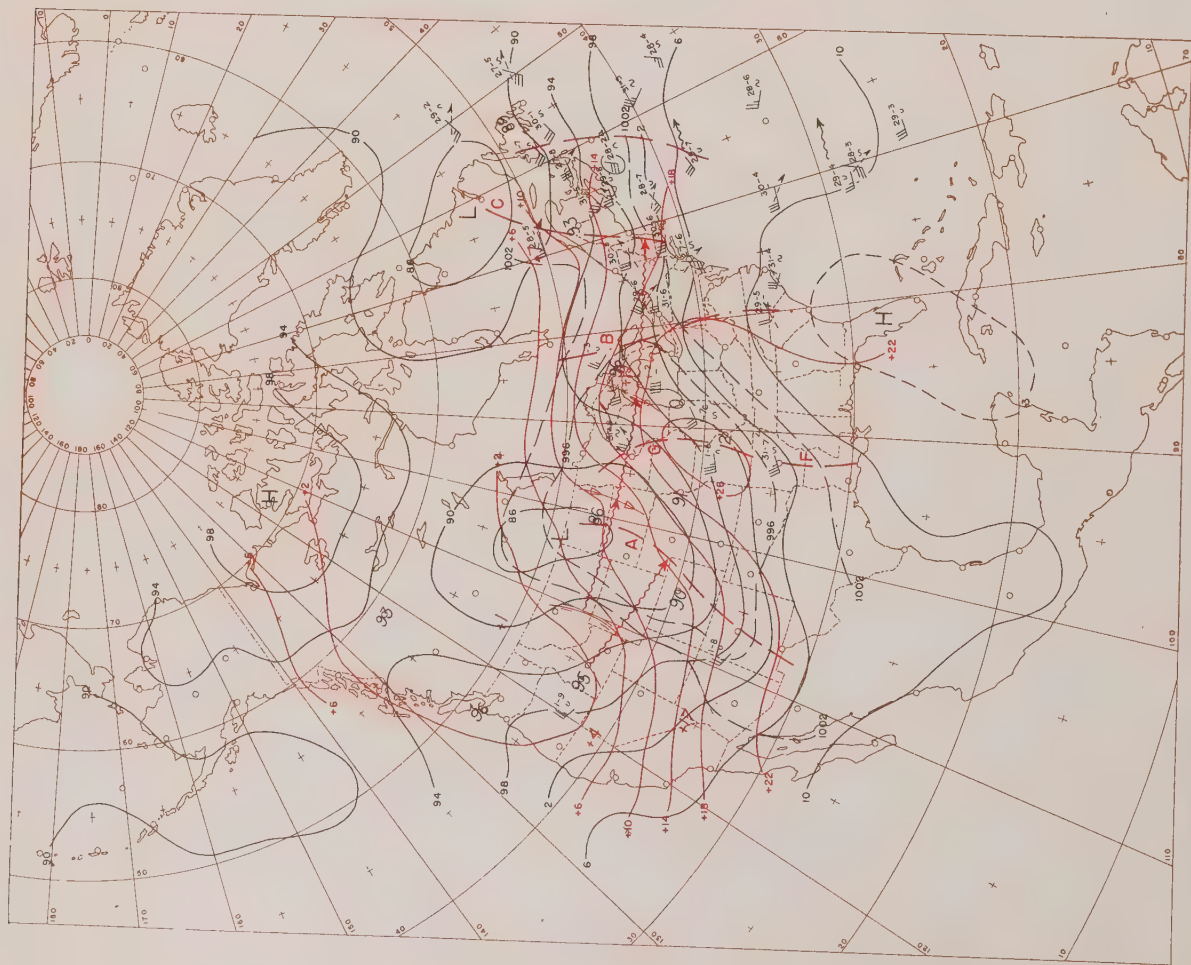


FIG. 45a. —Forecast Example: Prognostic 10,000-foot map for June 2, 1943, 2300 EST from June 1.

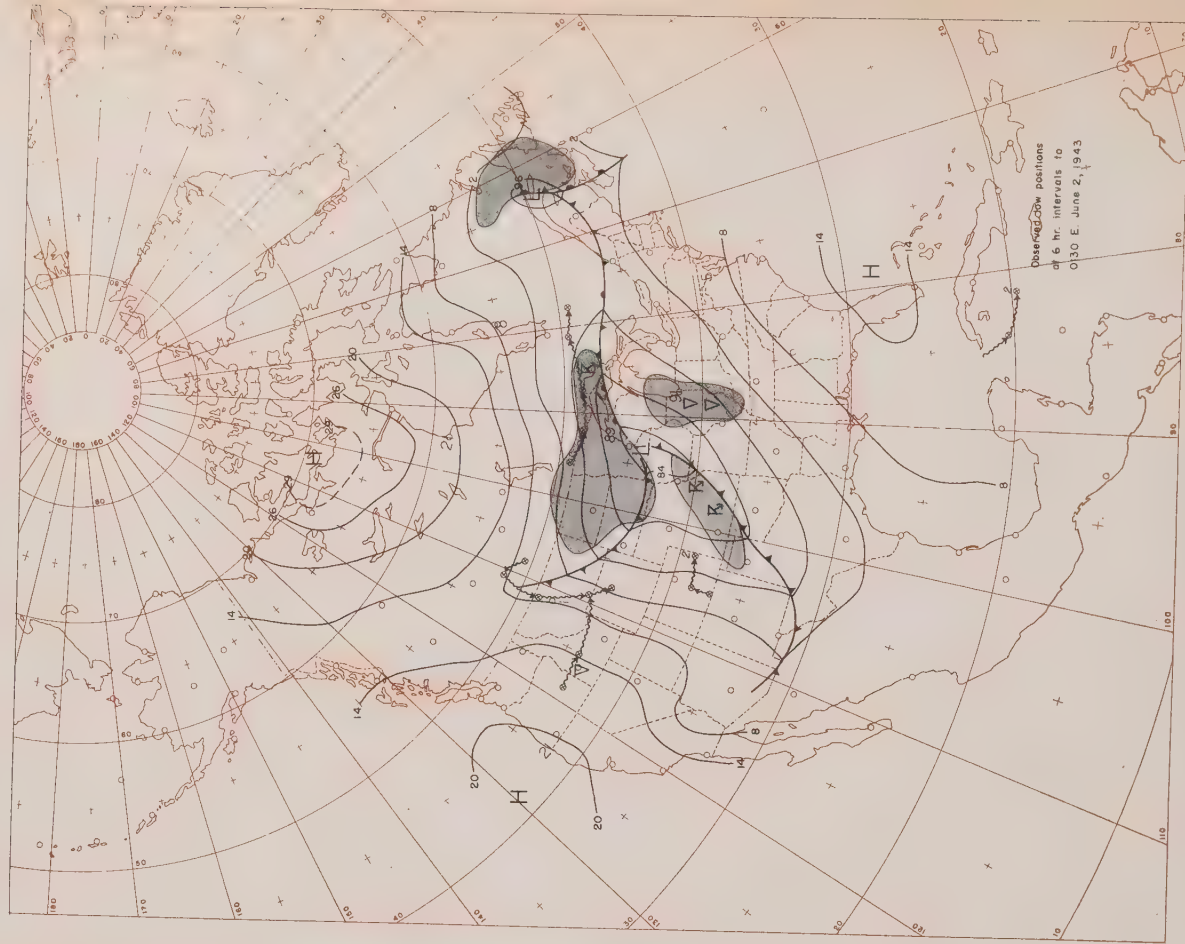


FIG. 45b. —Forecast Example: Prognostic surface map for June 3, 1943, 0130 EST from June 2.

is already a 10,000-foot low with considerable northerly flow to its rear; and there are indications of moderate pressure rises in the ridge off the coast. These processes are all corroborated at 10 km. With the general cyclonic conditions at the surface over the Plains and the Pp front with trough A approaching, followed by an extensive 12-hour pressure rise of 5 mb at the surface, everything is favorable for an active cyclonic development over the central United States. This development together with the 18° spacing of troughs A and C and the fact that ridge B is approaching the meridian of the almost stationary Florida high, indicate strengthening of the ridge.

In general, then, the 10,000-foot low was expected to deepen and move out over the Plains with accelerating upper flow around it. Because of this expected acceleration of the winds, trough A was moved 10° lat/day to the vicinity of Denver, with a velocity close to the initial maximum wind velocities instead of slightly less. Its position relative to wind 1-8 was thus left unchanged. There were no accurate past movements to assist this determination. The other important moving trough C, with the surface low above the Great Lakes, had good fixes both in the winds at the East Coast and in past movements. It was forecast to move slightly faster than past displacements and was given a normal easterly correction past the computed winds because of the circumstance that it was moving over a mean ridge and, moreover, had a mildly building ridge component behind. It was expected to move through on the middle circuit but not on the southern, since there it was definitely not vigorous enough to dislodge the eastern ridge and high. Between the ridge and trough A the several small troughs, especially G and F, were expected to combine into a SW trough on the 2d and give light showers in a small area near Chicago.

With the trough and ridge positions marked, estimates were next made of the 10,000-foot pressures for a few key stations in the main features of the pattern; these were based on the 24-hour pressure changes at 10,000 feet, the likely temperature changes, and the expected general isobar structure. Thus, an increase of the pressure fall in the main western trough complex was expected, with the Bismarck and Denver pressures dropping 9 and 5 mb, respectively, and falls of 3 to 4 mb extending to Chicago and St. Louis in the SW current. The pressure at Caribou was lowered 3 mb by uniform extrapolation of the pressure fall with trough C, and the Sault Ste Marie pressure was raised 2 mb because of the approach of ridge B and its pressure rise. Moderate to slight rises having already started were expected to continue in the almost stationary ridge off the West Coast, since there was no sign of a

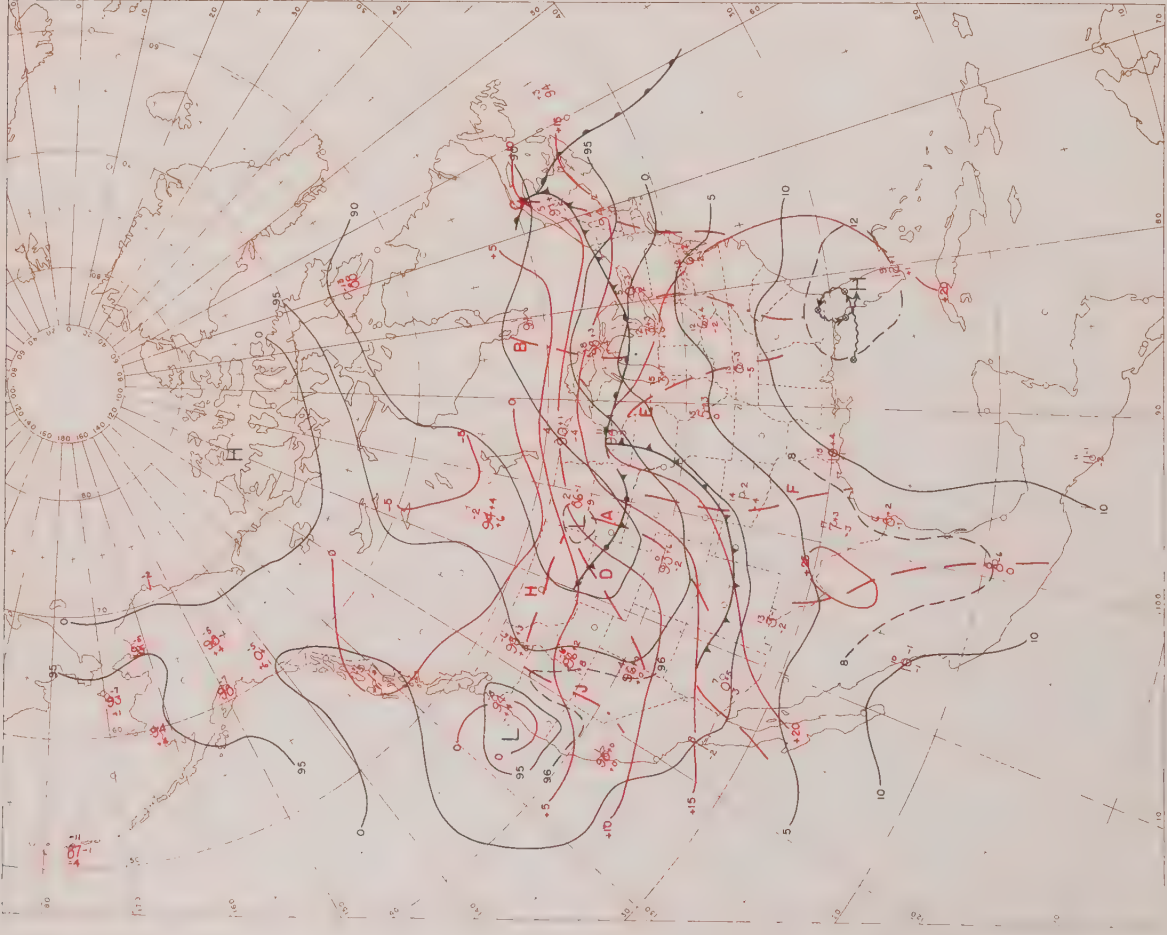


FIG. 45c.—Forecast Example: Observed 10,000-foot map for June 2, 1943, 2300 EST.

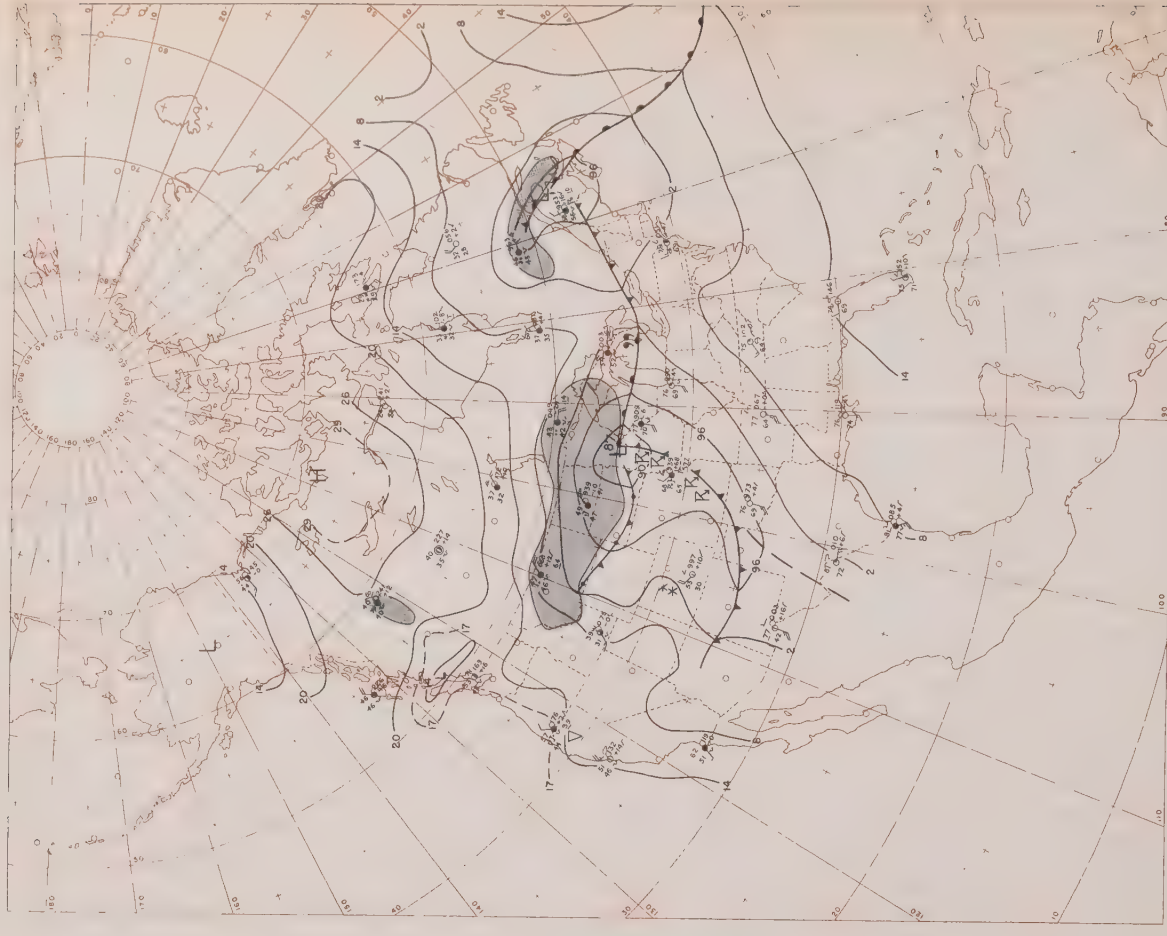


FIG. 45d.—Forecast Example: Observed surface map for June 3, 1943, 0130 EST.

surface low anywhere near the Gulf of Alaska, and rises extending in from the north in the upper high between Aklavik and Arctic Bay were expected to continue. With the aid of the winds and the trough and ridge positions the isobars were then drawn.

The same procedure of noting down values for a few key points before drawing isolines was used for the mean temperature. The values of $+17^{\circ}\text{C}$ and $+4^{\circ}\text{C}$ in the West were arrived at mainly from extrapolation of the temperature fall, the $+19^{\circ}\text{C}$ at Sault Ste Marie from the temperature rise, and the expected approach of the warm tongue. In the east the isotherms were displaced nearly advectively with the warm tongue in the normal relation to trough C; this called for a slight increase in the temperature fall behind the trough, which was considered likely. The principal mean-temperature warm tongue, which had been relatively stationary near the mountains, was expected to be dislodged by trough A, the amount of movement being determined from its relation to the trough, from the winds (averaging 7° to 9° lat/day), and from past displacement of the temperature rises. The 26°C mean isotherm in it was carried along for the first period with even a little increase expected because of the forecast vigor of the storm; but on the 2- and 3-day charts it was expected to disappear in accordance with the normal effect and the later preponderance of polar air around the low.

The forecast movement of the main warm tongue together with the surface 3-hourly pressure falls of up to 3 mb to the northeast of the surface low (though extremely restricted in area) and probable steering of the developing low by the SW upper current, indicated a movement for the low to near Minneapolis in the first 24 hours. The fronts in this low were fixed by reference to the upper troughs and from normal surface considerations, the approaching Pp front being expected to dissolve or at least amalgamate with the main cold front on the Plains. The secondary cold front was inserted mainly on the basis of surface indications of a more or less distinct air mass above the border and because of the probability of secondary troughs coming down around such a low development as this was expected to be.

If a piece of tracing paper is placed over Figure 45a, the implied surface isobars can be drawn by the intersection method (the isobars of 996 and 1002 mb are shown dashed as an aid). Having done this, let us compare the result with the final surface forecast in Figure 45b. There are two principal differences: (1) around the main low the pressures were held a little higher than those implied by the mean temperatures, since it seemed very difficult to see from the surface chart such large falls in a day this late in the season; and (2) the 1020 isobar was moved back toward the West Coast, since the Pp rise was considered not likely to continue so strong

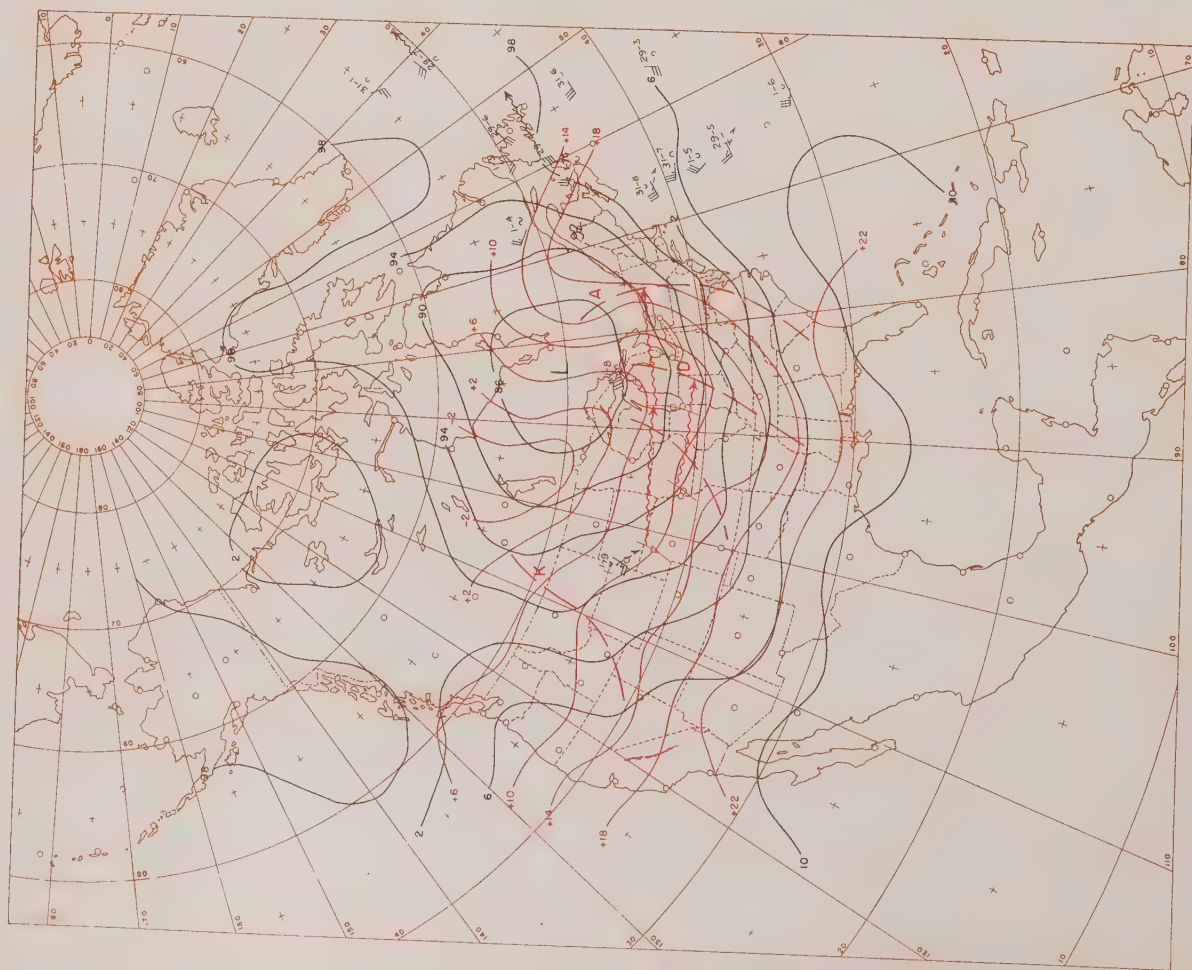


FIG. 46a.—Forecast Example: Prognostic 10,000-foot map for June 4, 1943, 2300 EST from June 1.

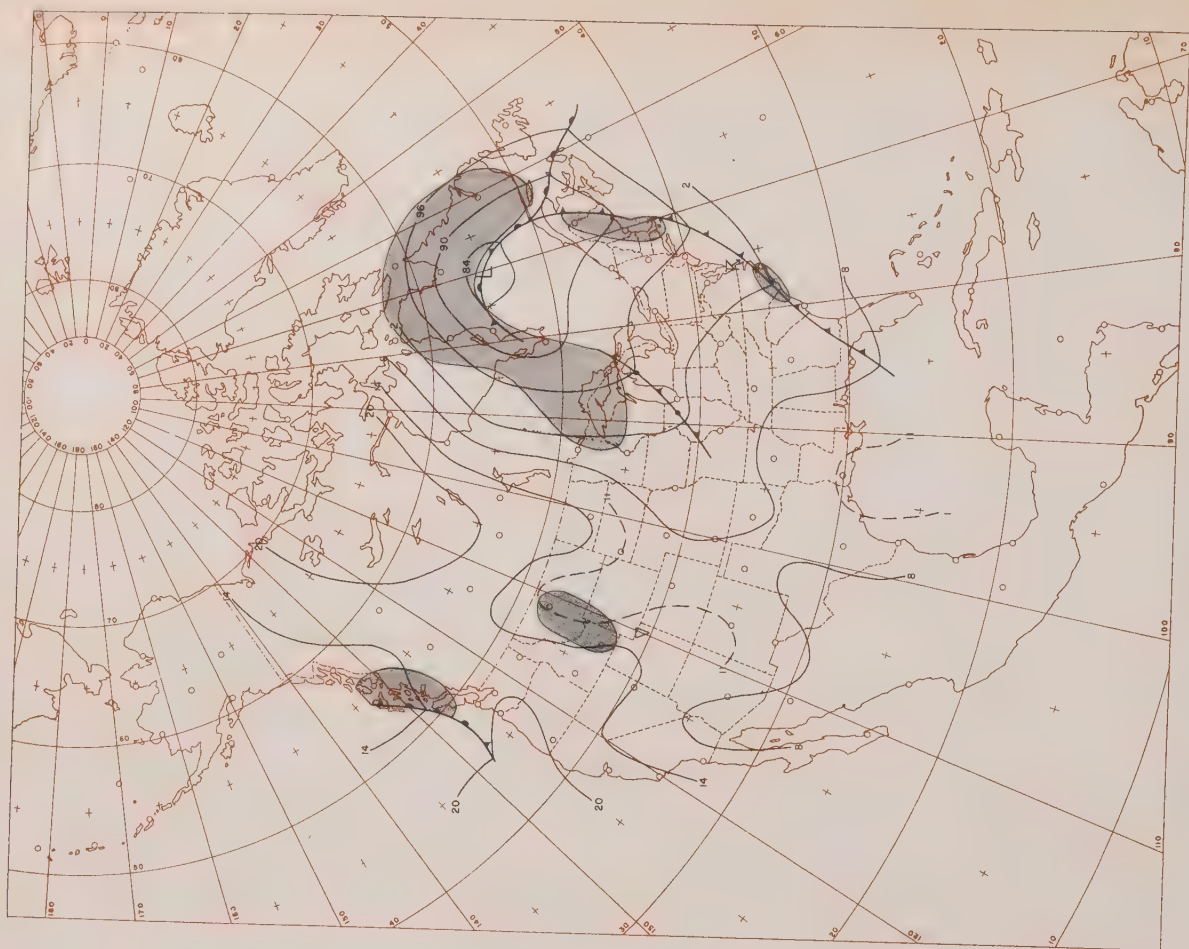


FIG. 46b.—Forecast Example: Prognostic surface map for June 5, 1943, 0130 EST from June 2.

inland. Since the mean isotherms in the West seemed correct, the error was thought to lie in the 10,000-foot pressures, which, however, were not changed.

On the 2- and 3-day charts, since this in general was expected to be a very vigorous development, troughs around the upper low were expected to extend well to the south and move fairly rapidly with the main cold front also extending all the way across the southern circuit. In view of the expected accelerations and extensive strong polar flow on the 10,000-foot chart, trough A was moved about 6° lat ahead of 1-8 on the 4th, and 1-9 was considered not likely to verify, though trough K was expected to have come across the western ridge by then. (The fact that there are only two trajectory winds in the United States on this 3-day chart is mainly due to the situation in the Gulf of Alaska prior to June 1, where an upper low was located at about 50° N with easterly winds over Alaska. There was consequently no way of determining any winds in the westerlies on which to make computations. Usually the westerlies extend farther north, and the coastal data are sufficient to draw isobars from which some winds can be selected.) In the East the winds 1-4 and 1-7c were forecast to verify SW because of the expected strength of the upper low, though their original directions would tend to indicate more predominance of the coastal ridge. The mean isotherms were carried through mainly by continuity with the two previous prognoses and on consistency with the expected 10,000-foot map. At the surface by this time the secondary front was to have overtaken the first cold front, and a new one was to be forming under the 10,000-foot mean trough on the forecast charts.

There are two major errors in these forecasts which by the third day have added up to such an extent that the day's maps are very poor. First, the entirely too wintry and drastic deepening expected of the principal low and, second, the failure to detect the formation of the western 10,000-foot low. The former error shows up even on the 24-hour chart to some extent and is very prominent on the 48- and 72-hour charts. The cold fronts were taken much too far south, and the breakdown of the high in the southeast which was predicated on this southerly movement does not occur. As a consequence of this, the mean isotherms were forecast too far south over the area around Illinois and too far north over New England on June 4. At the surface on the 4th, pressures are too low almost everywhere east of the Rockies; the single good feature is the only slightly too rapid movement of the cold front in New England. The failure to raise the surface pressures any more than was done in the Dakotas on June 4 is probably an inconsistency in the forecast, for, expecting as strong a low as we did with as extensive a surface high as was located in the District of Franklin in Canada initially, we should have forecast the high's draining down toward the south. The too low surface pressures

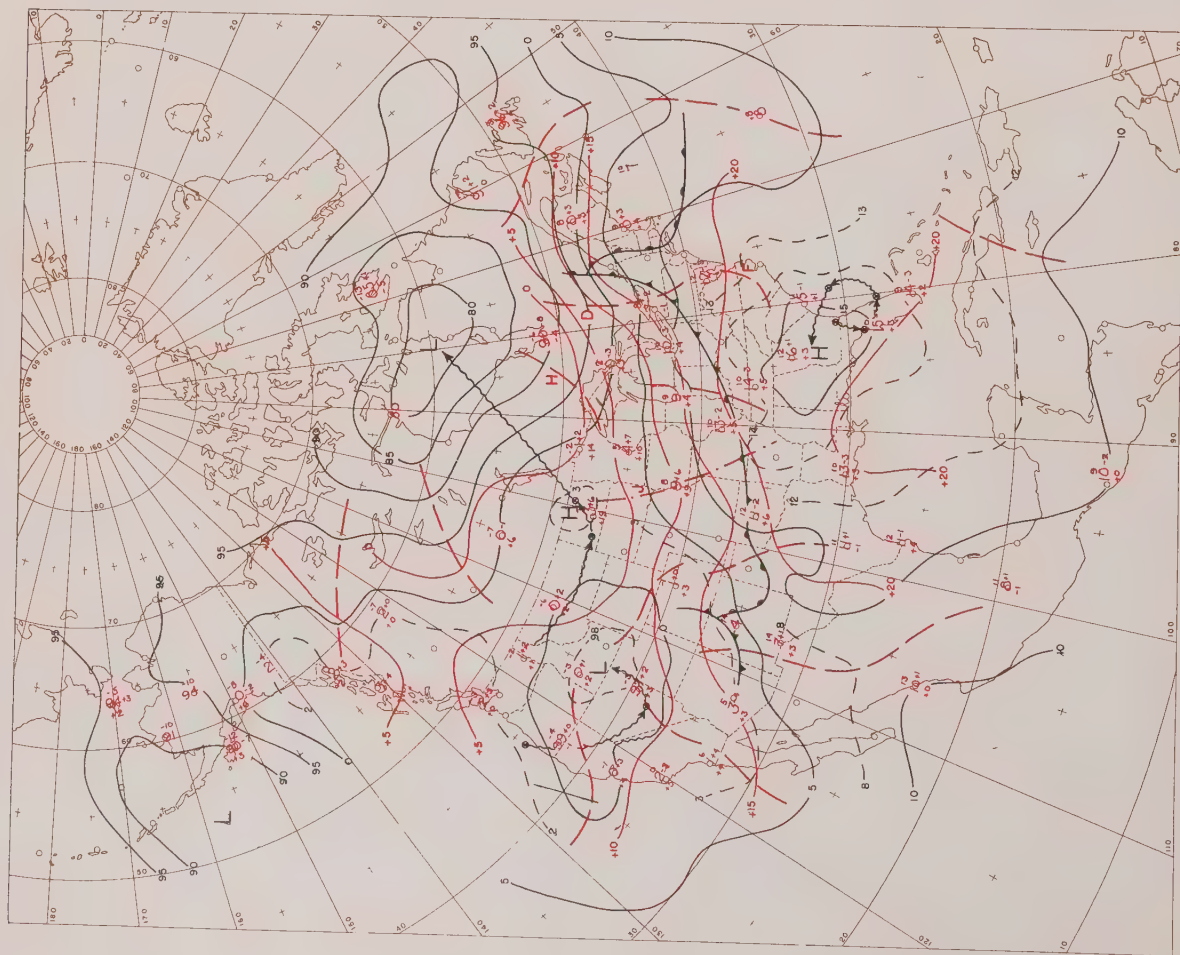


FIG. 46c.—Forecast Example: Observed 10,000-foot map for June 4, 1943, 2300 EST.



FIG. 46d.—Forecast Example: Observed surface map for June 5, 1943, 0130 EST.

on June 2 around the cyclone are partly due to expecting too much pressure fall too far south (connected with the first major error) and partly to displacing the 26° C mean isotherm as far as the Mississippi River—a thing which should not emphatically have been done.

It is difficult to see any way of detecting the development of the western 10,000-foot low without more Pacific data. This development is partly connected with the unexpectedly strong rises in the Gulf of Alaska ridge helped by rises continuing in the north toward Arctic Bay. Note that there was some indication in the wind 1-9 on the 4th particularly and in the secondary mean-temperature fall at Ketchikan on the 1st, but neither of these would be sufficient alone to justify such a drastic forecast. However, had the nearness to summer been realized fully, more weight would have been given to both these factors and not such a broad-scale low development would have been forecast in the east.

Summarizing: for 24 hours both the surface and the 10,000-foot maps are fair (except for the western upper low), but already there are differences which become great by June 4 and are primarily due to failure to place sufficient weight on the lateness of the season and on the significance of the pressure rises in the north and west.

2. Conclusions

The ultimate test of any procedure of the kind we have discussed lies in the weather forecasts and prognostic charts resulting from its use. It is obvious in what we have said that the trajectory principle in itself is entirely insufficient to yield these final results and that therefore the quality of the end product will depend in large measure on the other ingredients. However, despite all reservations, our feeling is that the trajectories (or the modifications which we could judge) on the whole have been a very definitely helpful element in the preparation of the prognostic charts.

By a standard of maximum usefulness, a good prognostic chart ought to verify all elements within one or two units (mb, degrees, hours) and positions within 1° or 2° lat. Needless to say, our series of prognostic charts in toto falls far short of qualifying as good by such a measure. Much of the procedure was developed in transit, and owing to the limitations of time, manpower, and data the prognostic series is far from complete. But by the end of the year definite improvement had become apparent, and considerable parts of many of the prognostic charts could be called good. As to the range of the forecasts, using roughly the methods we employed and provided there are adequate data from such areas as the Pacific, it can be said that a good set of 24-hour charts ought to be possible most of the time, fair 48-hour charts

a majority of the time, and reasonable 72-hour charts a large part of the time. Except in unusual cases, it is doubtful whether much consistent success would be obtained beyond 72 hours without some considerable additions to the forecasting principles we were able to use or were aware of.

While it would be very desirable for every prognostic chart to be really reliable, excellent use can often be made of charts which in certain respects turn out to be considerably in error. In particular for the difficult problem of timing, the trough and ridge positions at 10,000 feet can be a real help even when the forecast pressures in them are rather inaccurate. Fortunately these positions on our prognostic charts (especially those for two and three days) were considerably better than the pressure forecasts, on which more leeway can usually be tolerated. This might have been expected from the nature of the trajectory method, since it assists essentially only in prescribing the kinematic field and is of only indirect help for the pressures.

The usefulness of the prognostic charts will further depend upon the speed with which they can be completed, since it is obviously futile as a practical matter to spend 12 hours making a 24-hour prognostic chart. After the plotting and analysis of the 10,000-foot map, an experienced person can complete in little more than an hour the mechanical work, as now set up, on a dozen points extrapolated for six 24-hour periods, together with the plotting of the work sheets, the entry of the day's trough and ridge positions, and the checking of winds from previous days. The time then required to check auxiliary charts and complete the prognostic maps will depend upon the individual and upon the complexity of the particular situation, but under reasonable conditions will not be so long as to vitiate the results. If, however, communications are such that data are delayed or not available, or if the manpower at hand is insufficient to complete the many necessary routine tasks expeditiously, it may be more satisfactory not to perform the computations but merely to estimate paths and use (so far as they may succeed) the ideas we have outlined which do not depend upon the computations. As a matter of fact, after some practice, it is possible to estimate directly the 24-hour position very closely and the 48-hour position to considerable approximation for all ordinary conditions. These can be entered on any prognostic charts which may be drawn. This also provides an opportunity to allow directly for the deviations which may appear likely; and, indeed, such estimates should be made, even where computations are carried out, for winds which may not fit the required initial conditions or which for any reason are sufficiently in doubt as not to warrant a full calculation.

In the line of further work the following, in addition to points

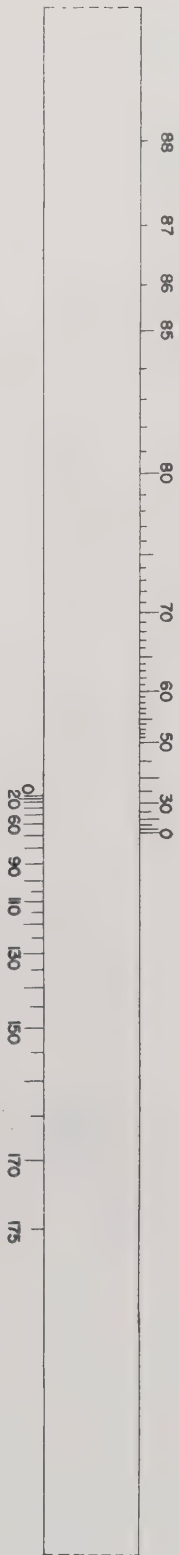
mentioned in preceding portions of the text, are suggested. J. Bjerknes' simple scheme for the distribution of divergence in low-pressure systems, where ahead of the trough is envisaged convergence in the lower levels and divergence above, suggests, since in the southwest winds we have seen a predominant convergence effect at 10,000 feet, that a slightly higher level, perhaps 15,000 feet, might be nearer the mean position of the level of non-divergence and might therefore give a distribution of deviations more evenly grouped about the C.A.V. path, rather than weighted on one side or the other as at 10,000 feet. In general, trajectories should be tried at several levels and efforts made to relate deviations at one level to currents and paths at the others and to find the relations of the trajectories to the streamline patterns at a number of heights.

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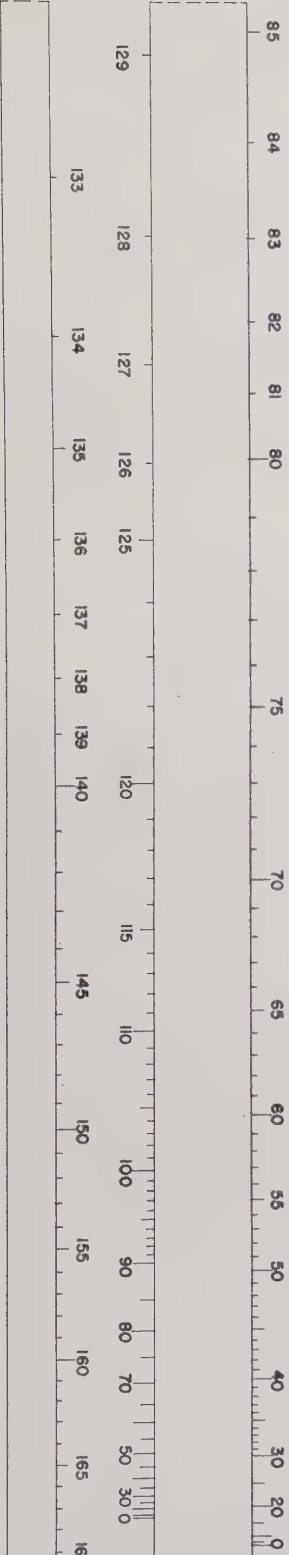
SLIDE RULE FOR CONSTANT VORTICITY TRAJECTORIES



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Y₁ [° Latitude]
Y_{max} [° Latitude]
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D [Longitude East]
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D [Longitude West]

SLIDE RULE

FOR

CONSTANT VORTICITY TRAJECTORIES

